Neutrino physics Beyond the SM

Enrique Fernández-Martínez

UAM Universidad Autonoma de Madrid

ift

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add N_R: a Majorana mass is also allowed

$$M_N \bar{N}_R N_R^c$$

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add N_R : a Majorana mass is also allowed

$$M_N \bar{N}_R N_R^c$$

This is an entirely new term which implies:

Fermion number violation → Baryogenesis via Leptogenesis

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add N_R: a Majorana mass is also allowed

$$M_N \overline{N}_R N_R^c$$

This is an entirely new term which implies:

Fermion number violation → Baryogenesis via Leptogenesis

The first mass scale not related to the EW scale and the Higgs

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add N_R: a Majorana mass is also allowed

$$M_N \overline{N}_R N_R^c$$

This is an entirely new term which implies:

Fermion number violation → Baryogenesis via Leptogenesis

The first mass scale not related to the EW scale and the Higgs

→ To be searched for at experiments!!

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add N_R: a Majorana mass is also allowed

$$M_N \overline{N}_R N_R^c$$

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add N_R : a Majorana mass is also allowed

$$M_N \overline{N}_R N_R^c$$

$$m_\nu = \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \longrightarrow U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

ν mass from right-handed neutrinos

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \bar{f}_R \phi f_L \xrightarrow[\langle\phi\rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_R f_L \qquad m_D = \frac{Y_f v}{\sqrt{2}}$$

Simplest option add N_R : a Majorana mass is also allowed

$$M_N \overline{N}_R N_R^c$$

$$m_\nu = \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \xrightarrow[\text{Seesaw}]{} U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

If $M_N \gg m_D$ then $M \approx M_N$ and $m \approx m_D^t M_N^{-1} m_D \rightarrow$ lightness of ν

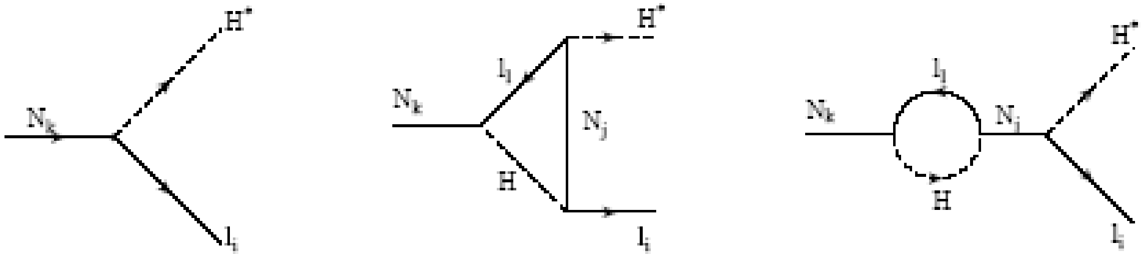
ν mass from right-handed neutrinos

$$m_\nu = \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \xrightarrow{\text{Seesaw}} U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

If $M_N \gg m_D$ then $M \approx M_N$ and $m \approx m_D^t M_N^{-1} m_D$ → lightness of ν

Leptogenesis

This simplest SM extension may connect to other open problems:

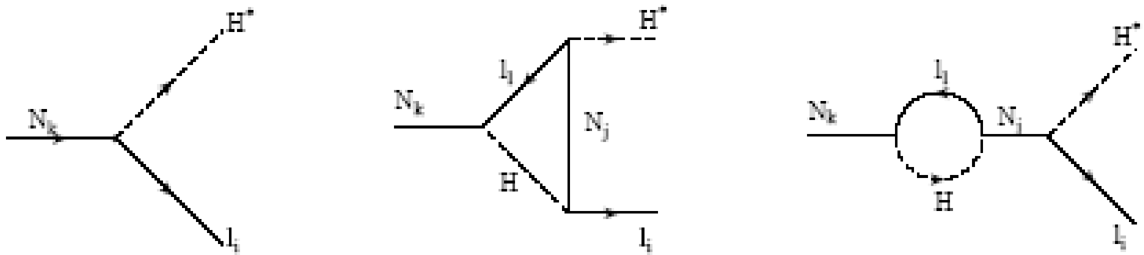


M. Fukugita and T. Yanagida 1986

-L is produced in the heavy N decays

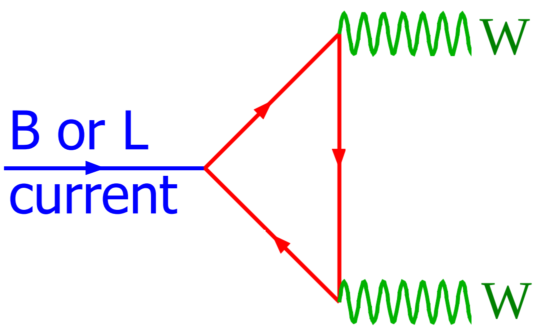
Leptogenesis

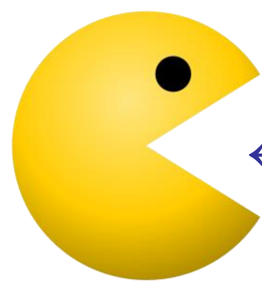
This simplest SM extension may connect to other open problems:



M. Fukugita and T. Yanagida 1986

-L is produced in the heavy *N* decays



B←  ← -L

and partially converted to B by the SM sphalerons

A new physics scale

But a very high M_N worsens the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)

A new physics scale

But a very high M_N worsens the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)

$$m_D \bar{N}_R \nu_L + M_N \bar{N}_R N_L$$

$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}$$

So that $m_\nu = 0$ even if $\Theta \approx m_D^\dagger M_N^{-1}$ is large

A new physics scale

But a very high M_N worsens the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)

$$m_D \bar{N}_R \nu_L + M_N \bar{N}_R N_L + \mu \bar{N}_L^c N_L$$

$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix}$$

"inverse Seesaw"

R. Mohapatra and J. Valle 1986

Small $m_\nu \approx \mu \dfrac{m_D^2}{M_N^2}$ even if $\Theta \approx m_D^\dagger M_N^{-1}$ is large and M_N low

Links with other open problems

With lower M_N possible connections with other open problems are easier to probe

ARS leptogenesis and DM possible in the νMSM

E. K. Akhmedov, V. A. Rubakov and A. Yu. Smirnov hep-ph/9803255

T. Asaka and M. Shaposhnikov hep-ph/0505013

Connexions with other open problems

With lower M_N possible connections with other open problems are easier to probe

ARS leptogenesis and DM possible in the νMSM

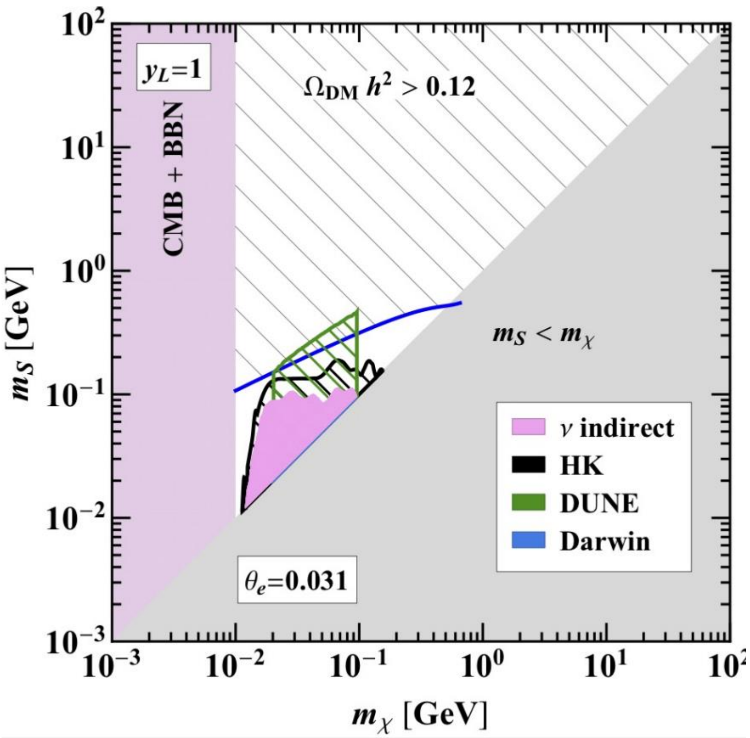
E. K. Akhmedov, V. A. Rubakov and A. Yu. Smirnov hep-ph/9803255

T. Asaka and M. Shaposhnikov hep-ph/0505013

But also neutrino portals to DM

M. Blennow, EFM, A. Olivares-Del Campo,

S. Pascoli, S. Rosauro arXiv:1903.00006



Connexions with other open problems

With lower M_N possible connections with other open problems are easier to probe

ARS leptogenesis and DM possible in the νMSM

E. K. Akhmedov, V. A. Rubakov and A. Yu. Smirnov hep-ph/9803255

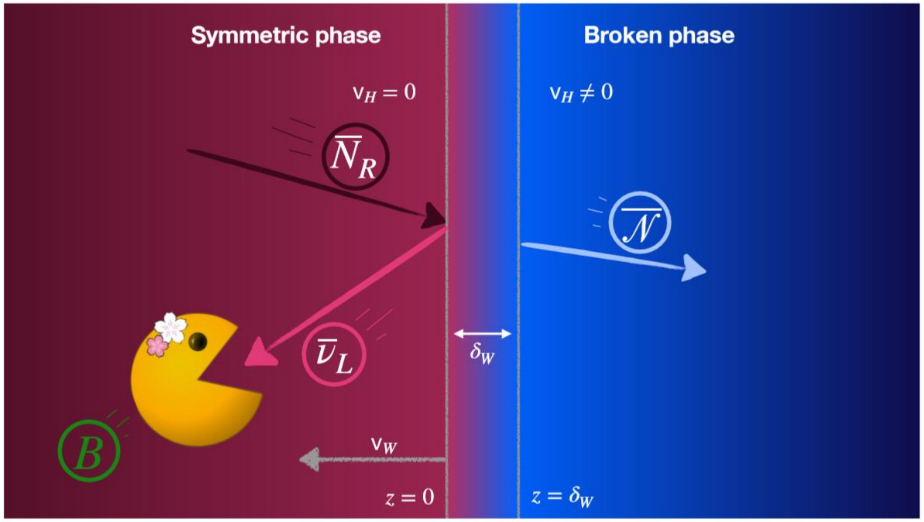
T. Asaka and M. Shaposhnikov hep-ph/0505013

But also neutrino portals to DM

M. Blennow, EFM, A. Olivares-Del Campo, S. Pascoli, S. Rosauro arXiv:1903.00006

Or other baryogenesis scenarios

See talk by Salvador Rosauro



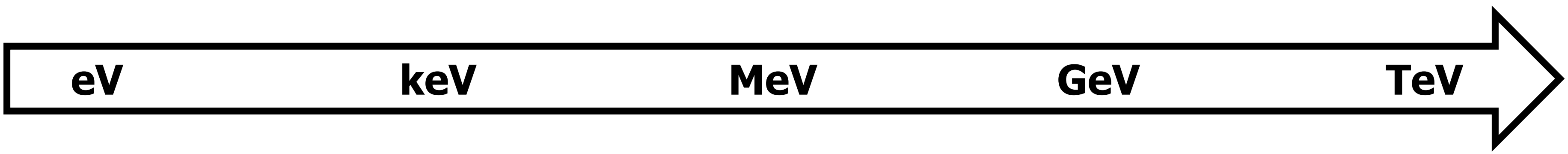
EFM, J. López-Pavón, T. Ota, S. Rosauro-Alcaraz arXiv: 2007.11008

also Stefan Sander, Garv Chauhan, Xunjie Xu, Kai Schmitz…

A new physics scale

But a very high M_N worsens the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)

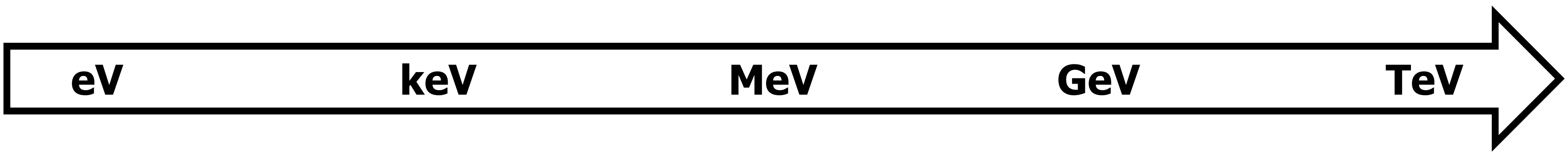


M_N could be anywhere…

A new physics scale

But a very high M_N worsens the Higgs hierarchy problem

Lightness of ν masses could also come naturally from an approximate symmetry (B-L)



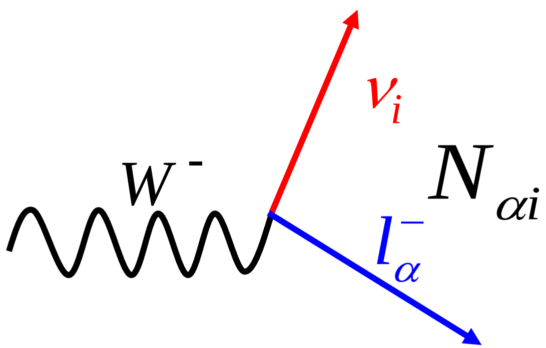
M_N could be anywhere…

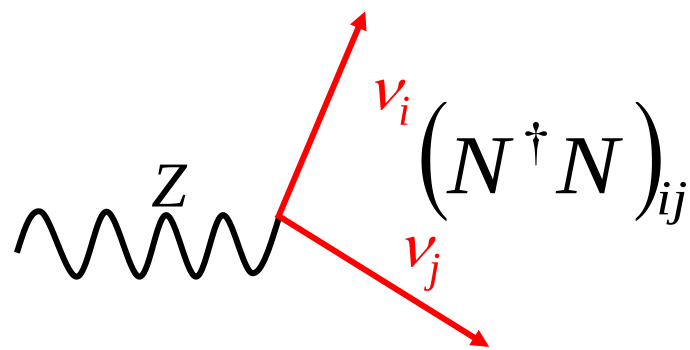
Very different phenomenology at different scales

Looking for N_R: Non-Unitarity

$$U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U \approx \begin{pmatrix} N^t & -\Theta^* \\ \Theta^t & X^t \end{pmatrix} \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The 3×3 submatrix N of active neutrinos will not be unitary



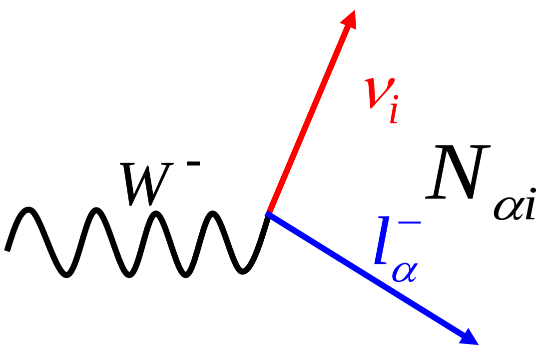


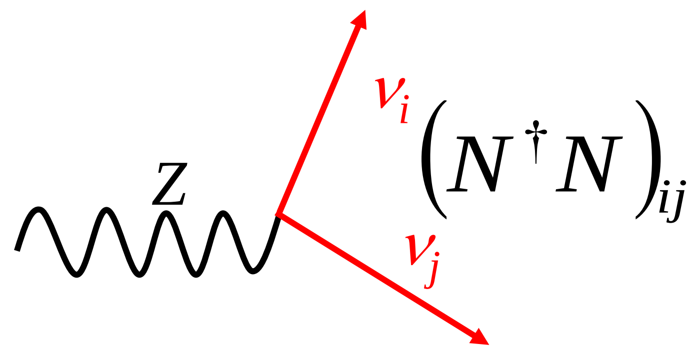
Effects in weak interactions…

Looking for N_R: Non-Unitarity

$$U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U \approx \begin{pmatrix} N^t & -\Theta^* \\ \Theta^t & X^t \end{pmatrix} \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The 3×3 submatrix N of active neutrinos will not be unitary





Effects in weak interactions…

When the W and Z are integrated out to obtain the Fermi theory NSI are recovered!

see e.g. M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637 for the dictionary

Non-unitarity in oscillations

Just replace U by N

$$P_{\alpha\beta}(L) = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-\Delta m^2_{ij} L}{2E}}$$

Non-unitarity in oscillations

Just replace U by N

$$P_{\alpha\beta}(L) = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-\Delta m^2_{ij} L}{2E}}$$

At $L=0$, $P_{\alpha\beta} \neq \delta_{\alpha\beta}$ this "zero distance effect" can be striking and is usually the source of the most stringent constraints

Non-unitarity in oscillations

Just replace U by N

$$P_{\alpha\beta}(L) = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-\Delta m^2_{ij} L}{2E}}$$

At $L=0$, $P_{\alpha\beta} \neq \delta_{\alpha\beta}$ this "zero distance effect" can be striking and is usually the source of the most stringent constraints

Careful!! These "probabilities" are not observables…

Non-unitarity in oscillations

Just replace U by N

$$P_{\alpha\beta}(L) = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-\Delta m^2_{ij} L}{2E}}$$

At $L=0$, $P_{\alpha\beta} \neq \delta_{\alpha\beta}$ this "zero distance effect" can be striking and is usually the source of the most stringent constraints

Careful!! These "probabilities" are not observables…

…they don't even add up to 1, not really probabilities!

Non-unitarity in oscillations

Just replace U by N

$$P_{\alpha\beta}(L) = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-\Delta m^2_{ij} L}{2E}}$$

At $L=0$, $P_{\alpha\beta} \neq \delta_{\alpha\beta}$ this "zero distance effect" can be striking and is usually the source of the most stringent constraints

Careful!! These "probabilities" are not observables…

…they don't even add up to 1, not really probabilities!

The "zero distance effect" will also be present in the data used to estimate the flux and cross section

Non-unitarity in oscillations

The real observable is the number of events

The measured probability $\hat{P}_{\mu e}(L)$ is the ratio of the events over the prediction from the flux and cross section in absence of oscillations

Non-unitarity in oscillations

The real observable is the number of events

The measured probability $\hat{P}_{\mu e}(L)$ is the ratio of the events over the prediction from the flux and cross section in absence of oscillations

For instance, if the prediction for $P_{\mu e}$ comes from near detector data on $P_{\mu\mu}$:

$$\hat{P}_{\mu e}(L) = \frac{P_{\mu e}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{ei} N^*_{\mu i} N_{\mu j} N^*_{ej}\, e^{\frac{-\Delta m^2_{ij} L}{2E}}}{\left|\left(NN^\dagger\right)_{\mu\mu}\right|^2}$$

Non-unitarity in oscillations

The real observable is the number of events

The measured probability $\hat{P}_{\mu e}(L)$ is the ratio of the events over the prediction from the flux and cross section in absence of oscillations

For instance, if the prediction for $P_{\mu e}$ comes from near detector data on $P_{\mu\mu}$:

$$\hat{P}_{\mu e}(L) = \frac{P_{\mu e}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{ei} N_{\mu i}^* N_{\mu j} N_{ej}^* e^{\frac{-\Delta m_{ij}^2 L}{2E}}}{\left|\left(NN^\dagger\right)_{\mu\mu}\right|^2}$$

Notice that, in general, this is different to normalizing as

$$|\nu_\alpha\rangle = \frac{N_{\alpha i}|\nu_i\rangle}{\sqrt{\left(NN^\dagger\right)_{\alpha\alpha}}}$$

M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Non-unitarity in oscillations

Also, no zero distance effect in disappearance channles!!

$$\hat{P}_{\mu\mu}(L) = \frac{P_{\mu\mu}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{\mu i} N_{\mu i}^* N_{\mu j} N_{\mu j}^* e^{\frac{-\Delta m_{ij}^2 L}{2E}}}{\left|\left(N N^\dagger\right)_{\mu\mu}\right|^2}$$

Non-unitarity in oscillations

Also, no zero distance effect in disappearance channles!!

$$\hat{P}_{\mu\mu}(L) = \frac{P_{\mu\mu}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{\mu i} N_{\mu i}^* N_{\mu j} N_{\mu j}^* e^{\frac{-\Delta m_{ij}^2 L}{2E}}}{\left| \left(N N^\dagger \right)_{\mu\mu} \right|^2}$$

These are often thought to be the strongest bounds, but the effect cancels when using actual data to predict the unoscillated events (which is always, think V_{ud})

Non-unitarity in oscillations

Also, no zero distance effect in disappearance channles!!

$$\hat{P}_{\mu\mu}(L) = \frac{P_{\mu\mu}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{\mu i} N^*_{\mu i} N_{\mu j} N^*_{\mu j} e^{\frac{-\Delta m^2_{ij} L}{2E}}}{\left|\left(N N^\dagger\right)_{\mu\mu}\right|^2}$$

These are often thought to be the strongest bounds, but the effect cancels when using actual data to predict the unoscillated events (which is always, think V_{ud})

At most, if the prediction comes from a different channel, one may constrain the ratio

$$\frac{\left|\left(N N^\dagger\right)_{\alpha\alpha}\right|^2}{\left|\left(N N^\dagger\right)_{\beta\beta}\right|^2}$$

Non-unitarity in oscillations

Also, no zero distance effect in disappearance channles!!

$$\hat{P}_{\mu\mu}(L) = \frac{P_{\mu\mu}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{\mu i} N_{\mu i}^* N_{\mu j} N_{\mu j}^* e^{\frac{-\Delta m_{ij}^2 L}{2E}}}{\left|\left(NN^\dagger\right)_{\mu\mu}\right|^2}$$

These are often thought to be the strongest bounds, but the effect cancels when using actual data to predict the unoscillated events (which is always, think V_{ud})

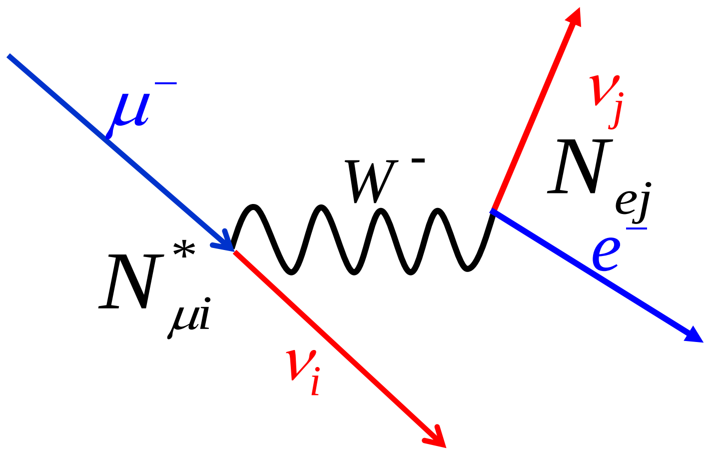
At most, if the prediction comes from a different channel, one may constrain the ratio

$$\frac{\left|\left(NN^\dagger\right)_{\alpha\alpha}\right|^2}{\left|\left(NN^\dagger\right)_{\beta\beta}\right|^2}$$

But these are more efficiently constraint from LFU bounds, from instance π decay ratios, no need to also detect the ν…

Non-unitarity beyond oscillations

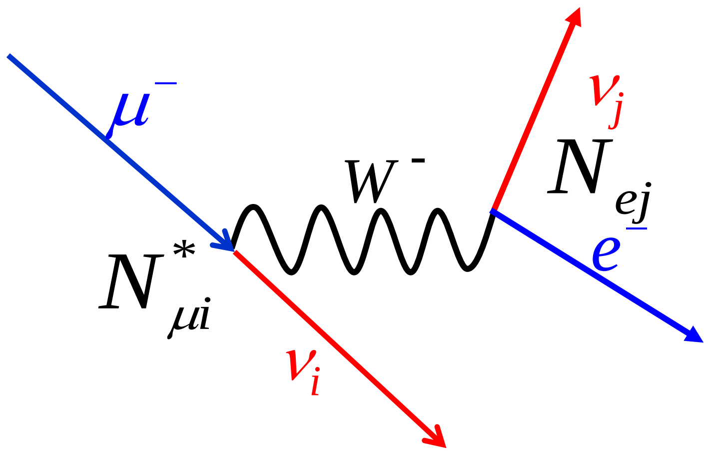
G_F from μ decay is affected!



$$G_\mu = G_F \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$$

Non-unitarity beyond oscillations

G_F from μ decay is affected!

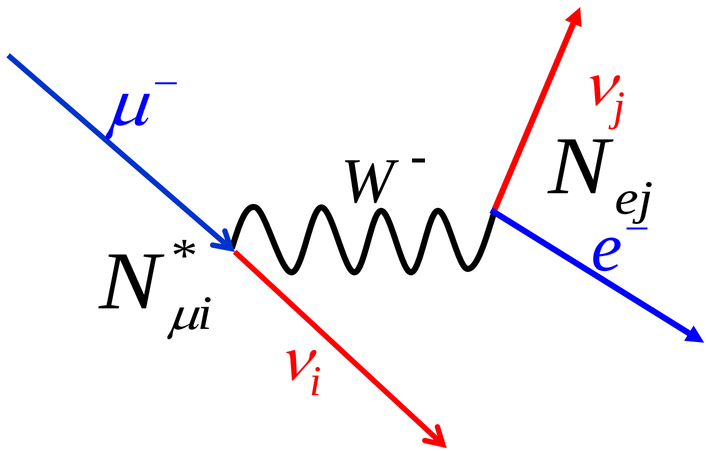


$$G_\mu = G_F \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$$

But this agrees at $\sim 10^{-3}$ with G_F from M_W (modulo CDF), measurents of $\sin\theta_W$ from LEP, Tevatron and LHC and β and K decays

Non-unitarity beyond oscillations

G_F from μ decay is affected!



$$G_\mu = G_F \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$$

But this agrees at $\sim 10^{-3}$ with G_F from M_W (modulo CDF), measurents of $\sin\theta_W$ from LEP, Tevatron and LHC and β and K decays

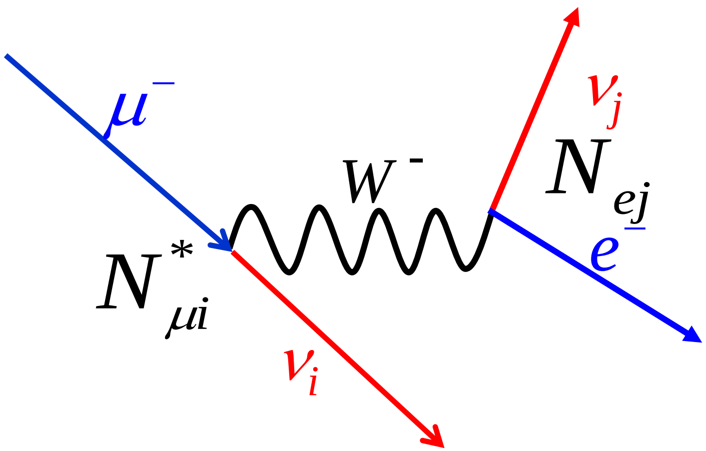
LFU also strong bounds on ratios:

$$\frac{\left(NN^\dagger\right)_{\alpha\alpha}}{\left(NN^\dagger\right)_{\beta\beta}}$$

From ratios of π, K, and lepton decays

Non-unitarity beyond oscillations

G_F from μ decay is affected!



$$G_\mu = G_F \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$$

But this agrees at $\sim 10^{-3}$ with G_F from M_W (modulo CDF), measurents of $\sin\theta_W$ from LEP, Tevatron and LHC and β and K decays

LFU also strong bounds on ratios:

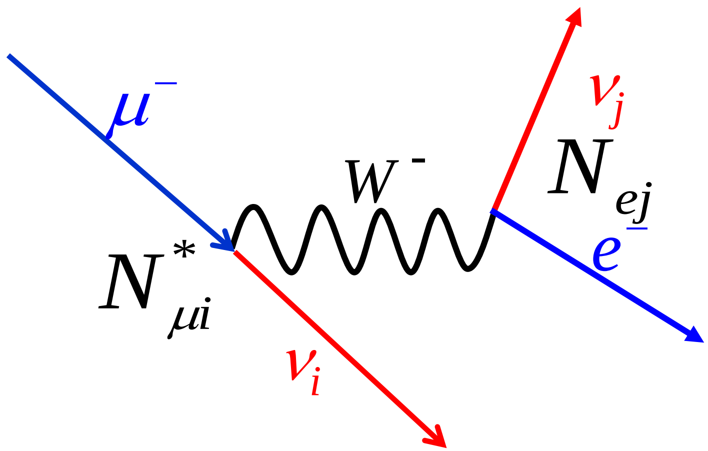
$$\frac{\left(NN^\dagger\right)_{\alpha\alpha}}{\left(NN^\dagger\right)_{\beta\beta}}$$

From ratios of π, K, and lepton decays

Also the invisible width of the Z since NC are also affected

Non-unitarity beyond oscillations

G_F from μ decay is affected!



$$G_\mu = G_F \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$$

But this agrees at $\sim 10^{-3}$ with G_F from M_W (modulo CDF), measurents of $\sin\theta_W$ from LEP, Tevatron and LHC and β and K decays

LFU also strong bounds on ratios:

$$\frac{\left(NN^\dagger\right)_{\alpha\alpha}}{\left(NN^\dagger\right)_{\beta\beta}}$$

From ratios of π, K, and lepton decays

Also the invisible width of the Z since NC are also affected

And LFV processes such as $\mu \to e\,\gamma$ since the GIM cancellation is lost

Looking for N_R: Non-Unitarity

Bounds from a global fit to flavour and Electroweak precision data

	"flavor+electroweak" $m >$ EW (2σ limit)
α_{ee}	$1.4 \cdot 10^{-3}$
$\alpha_{\mu\mu}$	$1.4 \cdot 10^{-4}$
$\alpha_{\tau\tau}$	$8.8 \cdot 10^{-4}$
$\lvert\alpha_{\mu e}\rvert$	$7.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$)
$\lvert\alpha_{\tau e}\rvert$	$1.8 \cdot 10^{-3}$
$\lvert\alpha_{\tau\mu}\rvert$	$4.8 \cdot 10^{-4}$

with

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ -\alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ -\alpha_{\tau e} & -\alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U$$

Z.-z. Xing 0709.2220 and 1110.0083. F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1503.08879.

M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero and J. Lopez-Pavon in preparation

See also P. Langaker and D. London 1988; S. M. Bilenky and C. Giunti hep-ph/9211269 ; E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228; D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228; S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020; S. Antusch, J. Baumann and EFM 0807.1003; D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle 1107.6009; S. Antusch and O. Fischer 1407.6607; F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774…

Looking for N_R: Non-Unitarity

Bounds from a global fit to flavour and Electroweak precision data

	"flavor+electroweak" $m >$ EW (2σ limit)	Oscillations (from zero distance effects in disappearance, 90%)
α_{ee}	$1.4 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$ [55]
$\alpha_{\mu\mu}$	$1.4 \cdot 10^{-4}$	$5.0 \cdot 10^{-3}$ [15]
$\alpha_{\tau\tau}$	$8.8 \cdot 10^{-4}$	$6.5 \cdot 10^{-2}$ [56]
$\lvert\alpha_{\mu e}\rvert$	$7.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$)	$9.2 \cdot 10^{-3}$
$\lvert\alpha_{\tau e}\rvert$	$1.8 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$4.8 \cdot 10^{-4}$	$1.1 \cdot 10^{-2}$

From C. Argüelles et al Snowmass Whitepaper arXiv:2203.10811 and M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero and J. Lopez-Pavon in preparation

with

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ -\alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ -\alpha_{\tau e} & -\alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U$$

Looking for N_R: Non-Unitarity

It has become common to call them:

"Indirect" or "charged leptons" — "Direct" or "neutrinos"

	"flavor+electroweak" $m >$ EW (2σ limit)	Oscillations (from zero distance effects in disappearance, 90%)
α_{ee}	$1.4 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$ [55]
$\alpha_{\mu\mu}$	$1.4 \cdot 10^{-4}$	$5.0 \cdot 10^{-3}$ [15]
$\alpha_{\tau\tau}$	$8.8 \cdot 10^{-4}$	$6.5 \cdot 10^{-2}$ [56]
$\|\alpha_{\mu e}\|$	$7.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$9.2 \cdot 10^{-3}$
$\|\alpha_{\tau e}\|$	$1.8 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
$\|\alpha_{\tau\mu}\|$	$4.8 \cdot 10^{-4}$	$1.1 \cdot 10^{-2}$

From C. Argüelles et al Snowmass Whitepaper arXiv:2203.10811 and M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero and J. Lopez-Pavon in preparation

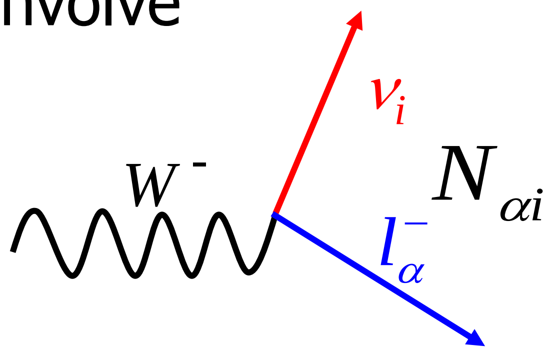
Looking for N_R: Non-Unitarity

It has become common to call them:

"Indirect" or "charged leptons"

"Direct" or "neutrinos"

But they all involve



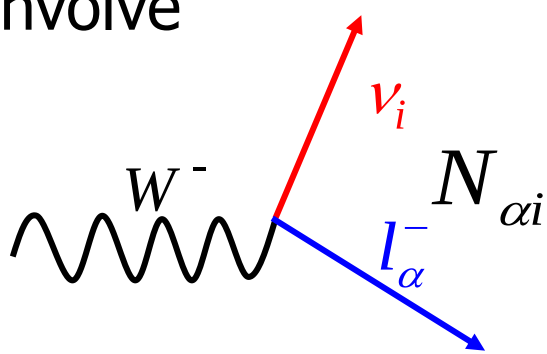
Looking for N_R: Non-Unitarity

It has become common to call them:

"Indirect" or "charged leptons"

"Direct" or "neutrinos"

But they all involve



it's where the sensitivity comes from…

So they are all equally "direct" and they all have a neutrino and a charged lepton…

Looking for N_R: Non-Unitarity

Which one is more robust/model-independent?

"Indirect" or "charged leptons"

"Direct" or "neutrinos"

Looking for N_R: Non-Unitarity

Which one is more robust/model-independent?

"Indirect" or "charged leptons"

"Direct" or "neutrinos"

↓

Introducing an NSI operator with u and d quarks the zero distance effect could be cancelled

Looking for N_R: Non-Unitarity

Which one is more robust/model-independent?

"Indirect" or "charged leptons"

"Direct" or "neutrinos"

↓

Introducing an NSI operator with u and d quarks the zero distance effect could be cancelled

They also come from zero-distance effect…

Looking for N_R: Non-Unitarity

Which one is more robust/model-independent?

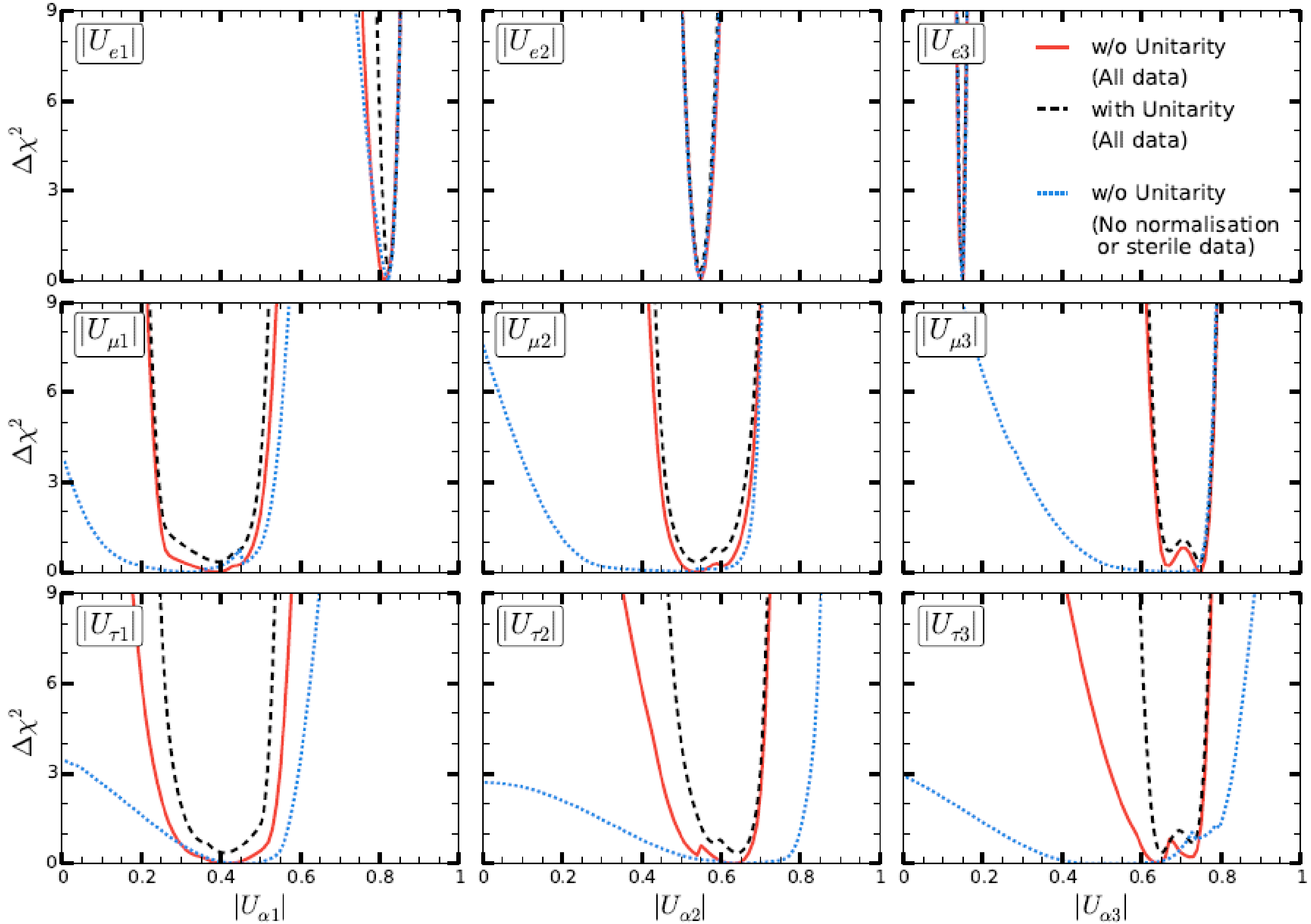
"Indirect" or "charged leptons" → G_F from μ decay compared to from M_W, measurements of $\sin\theta_w$ at different energies (Moller, colliders) and β and K decays. Very different physics!

"Direct" or "neutrinos" → Introducing an NSI operator with u and d quarks the zero distance effect could be cancelled
They also come from zero-distance effect…

But in the literature the "neutrino" bounds are assumed to be more robust…

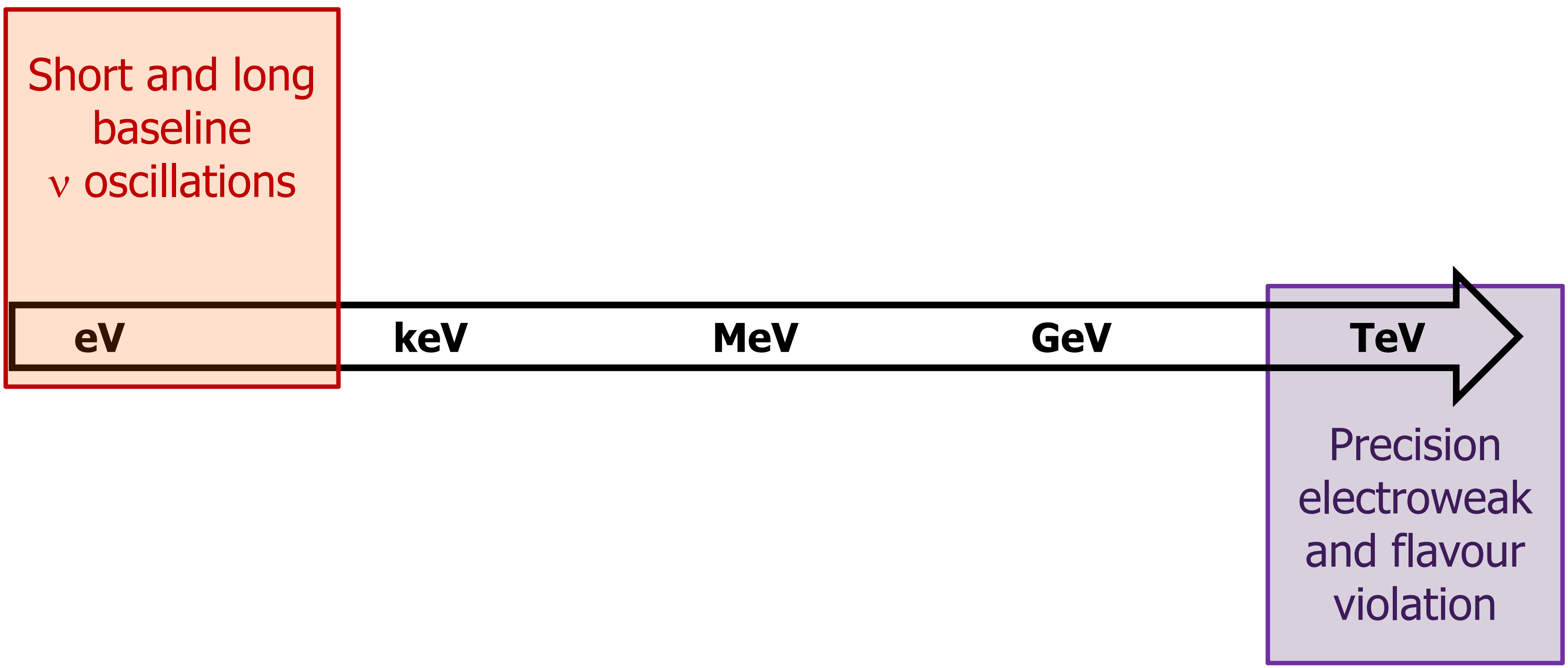
The only? Way out: lighter Steriles

For very light (< keV) extra neutrinos these strong constraints are lost and ν oscillations are our best probe of this scale.



S. Parke and M. Ross-Lonergan arXiv:1508.05095

A new physics scale



Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637
C. S. Fong, H. Minakata and H. Nunokawa arXiv:1609.08623

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}} + \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}} + \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{iJ} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637
C. S. Fong, H. Minakata and H. Nunokawa arXiv:1609.08623

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}}$$

$$+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{iJ} L}{2E}}$$

If $\frac{\Delta m^2_{ij} L}{2E} \gg 1$ oscillations too fast to resolve and only see average effect

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1609.08637
C. S. Fong, H. Minakata and H. Nunokawa 1609.08623

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}} + \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}}$$

At leading order "heavy" non-unitarity and avergaed-out "light" steriles have the same impact in oscillations

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix}$$

"Heavy ν" Non-Unitarity

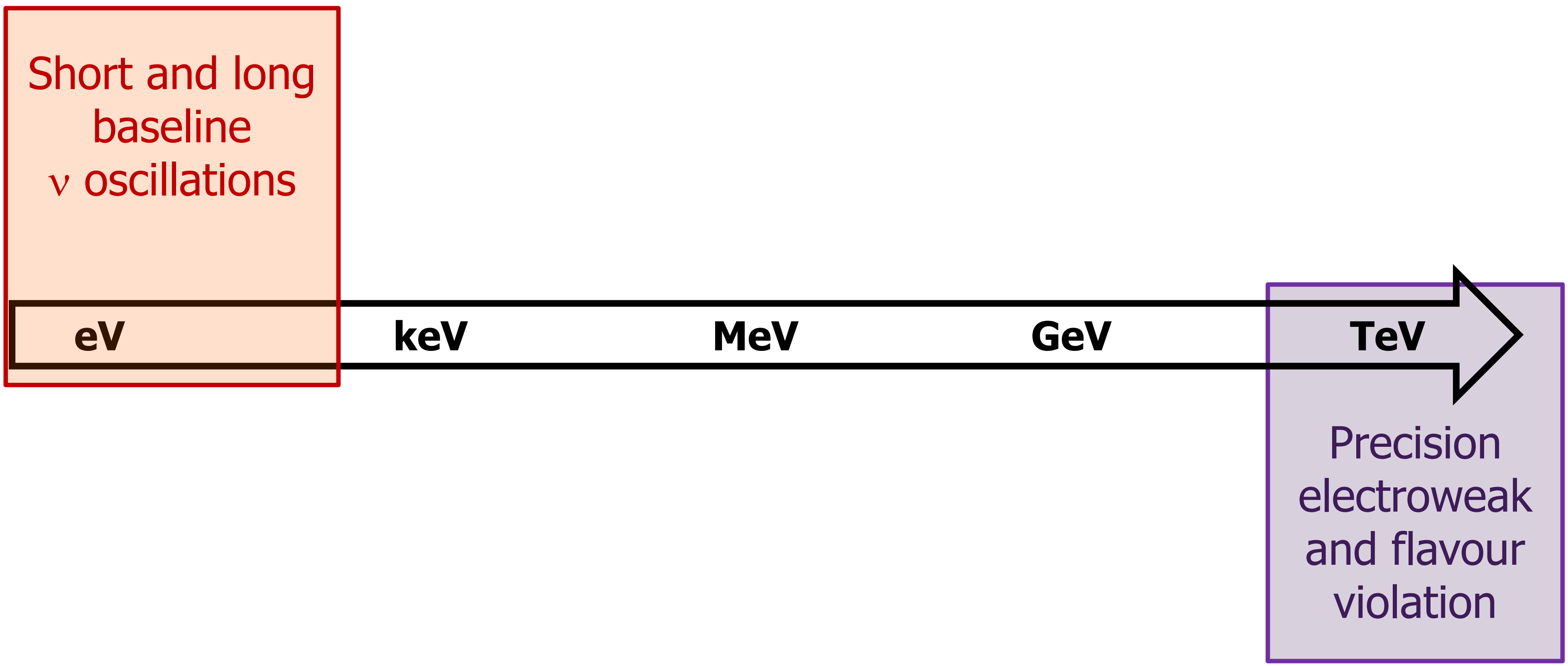
$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

"Light ν" Steriles

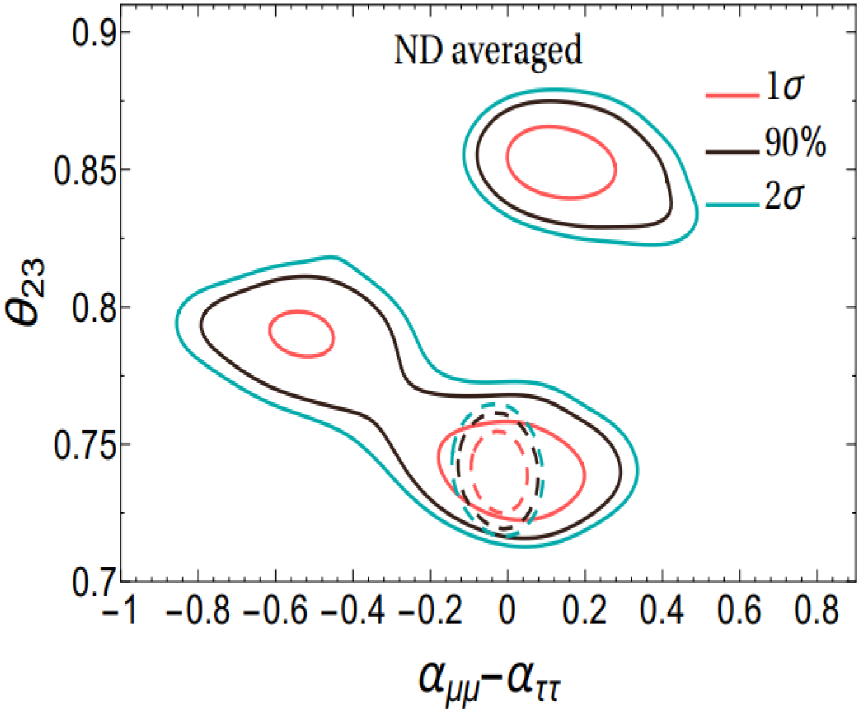
$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

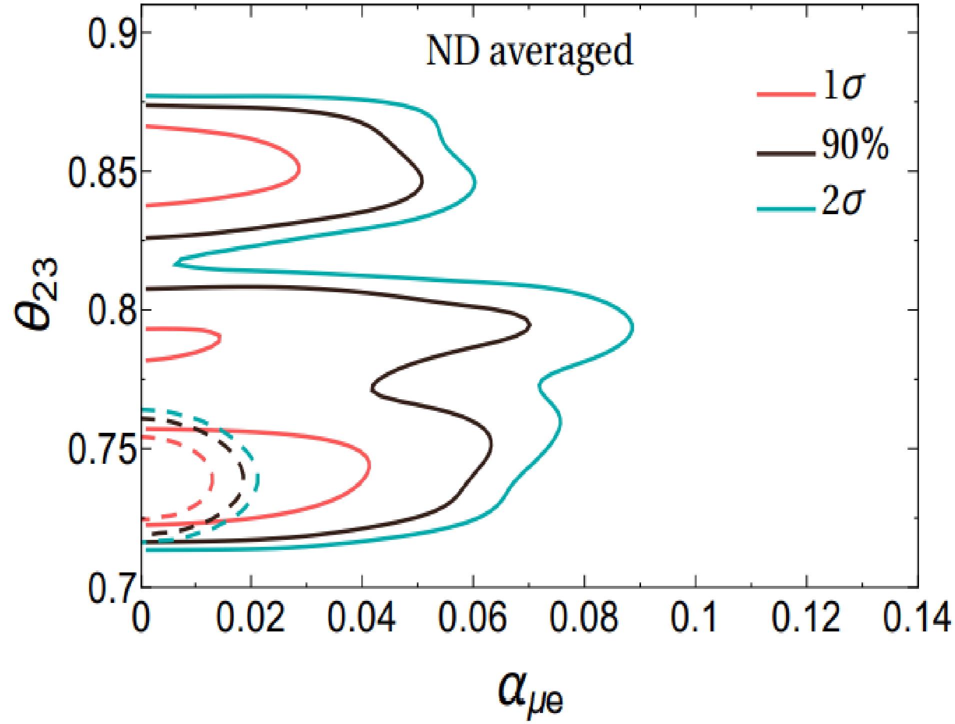
If $\frac{\Delta m^2_{ij} L}{2E} \ll 1$ at the near detector or in the data to estimate the flux and cross section, the zero distance effect is recovered and bounds apply

A new physics scale



Non-unitarity at DUNE

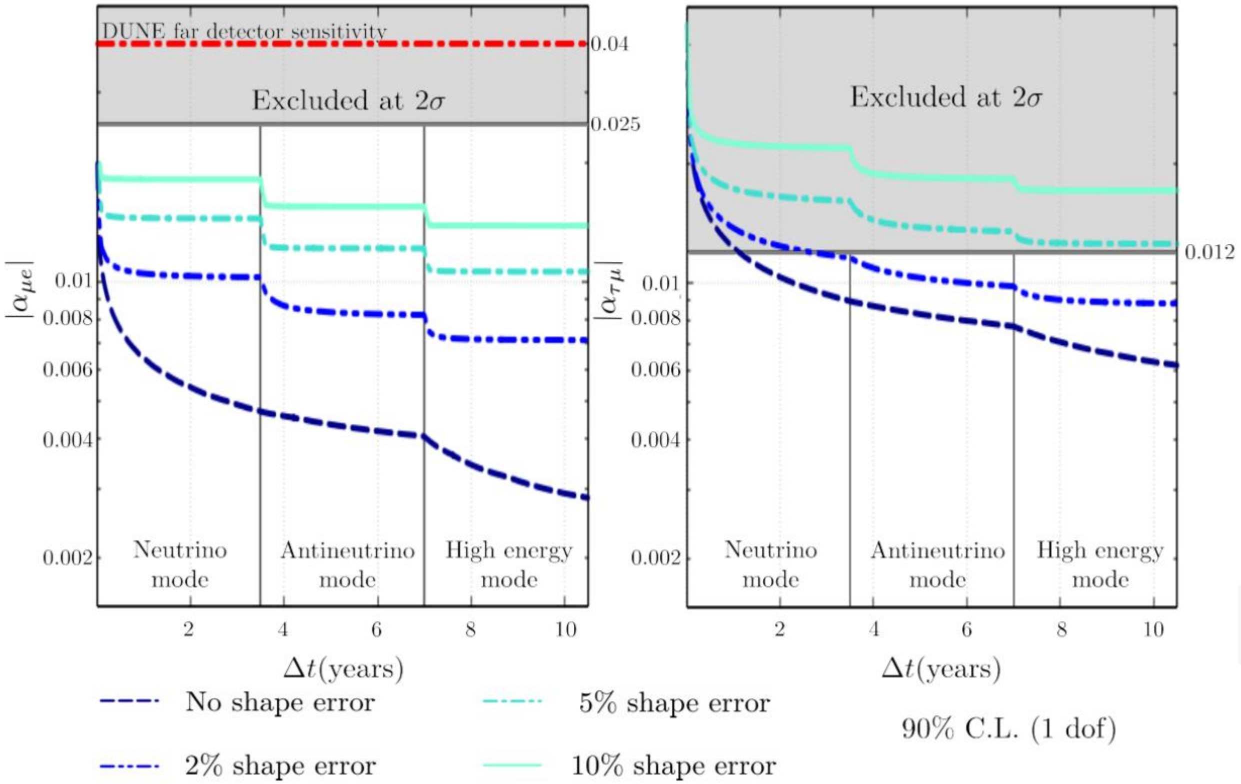




The far detector would suffer from degeneracies but they are lifted with present bounds

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

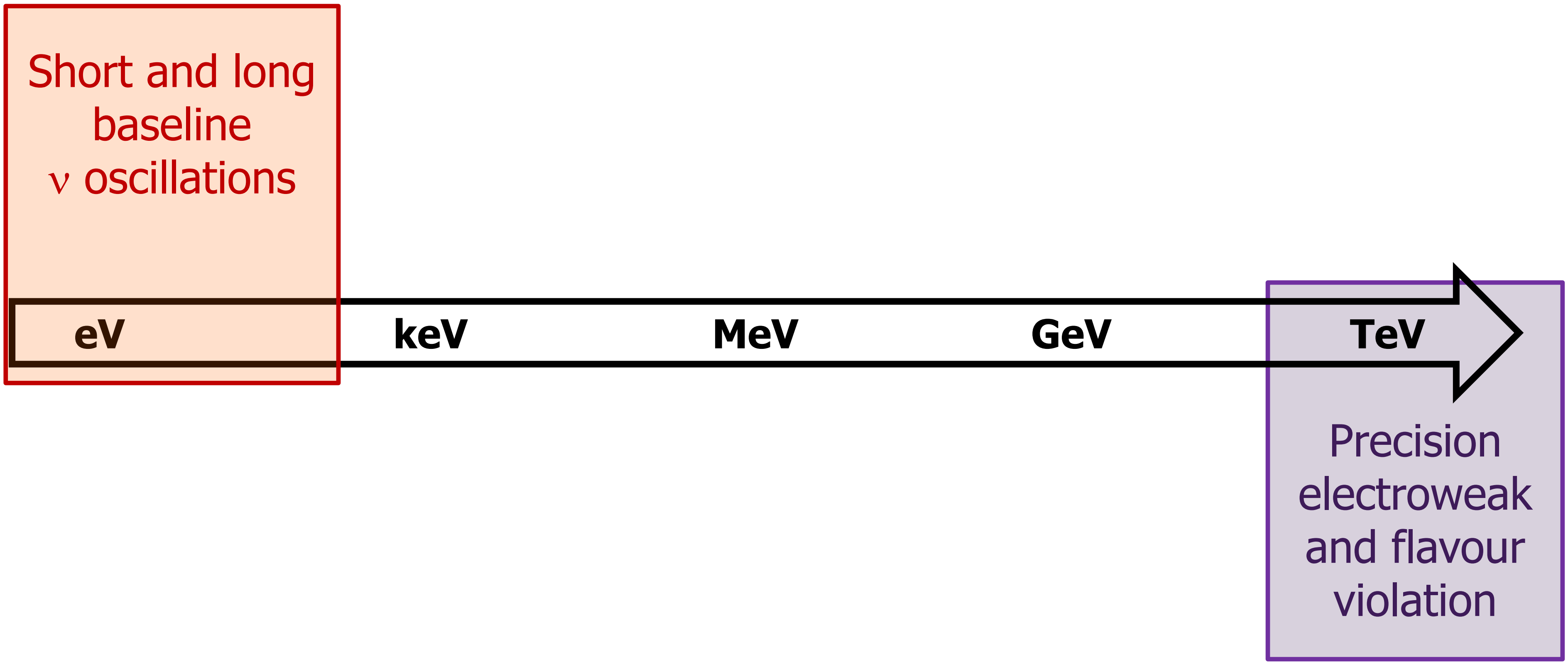
Non-unitarity at DUNE



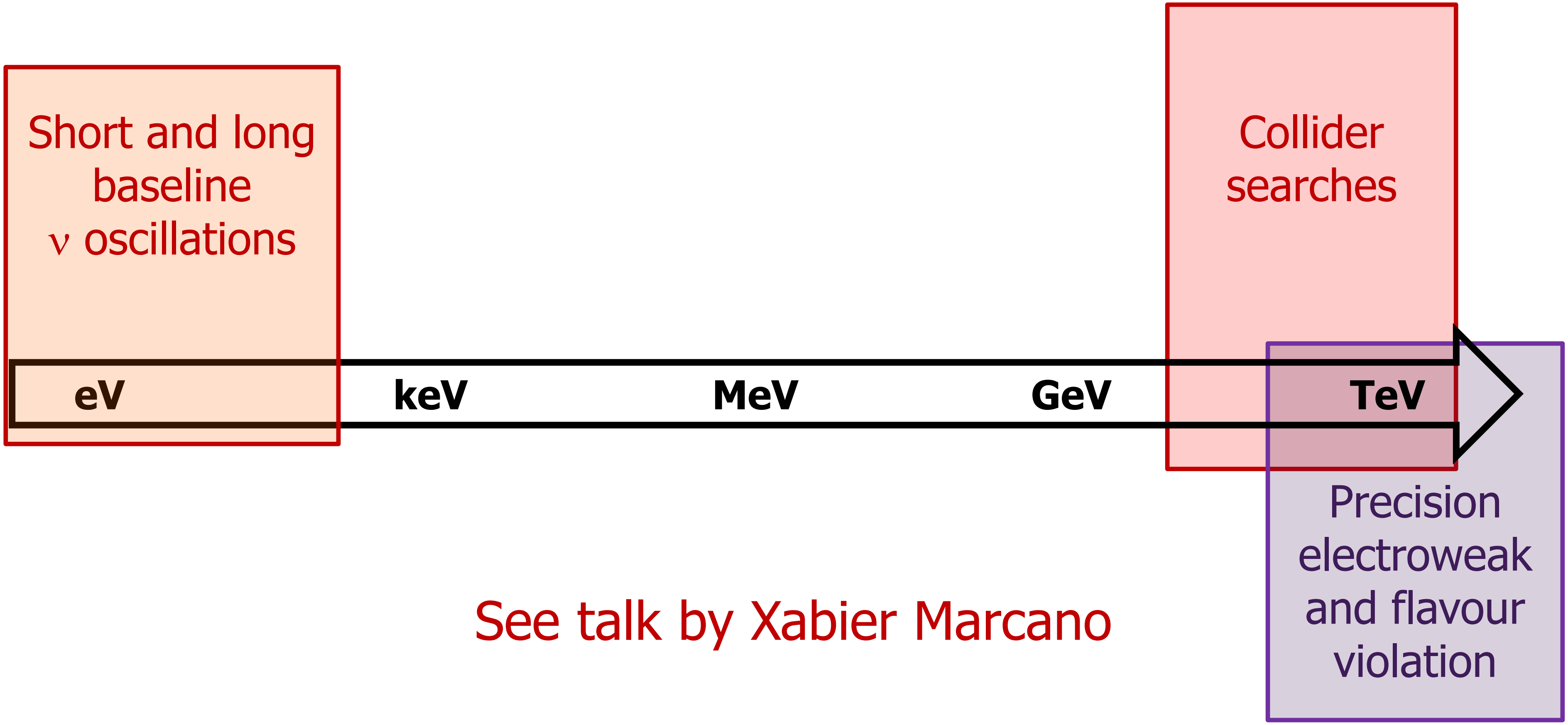
The posible improvements by the near detector depend critically on the level of systematic uncertainties, particularly affecting the shape of the spectra

P. Coloma, J. Lopez-Pavon, S. Rosauro-Alcaraz and S. Urrea arXiv:2105.11466

A new physics scale

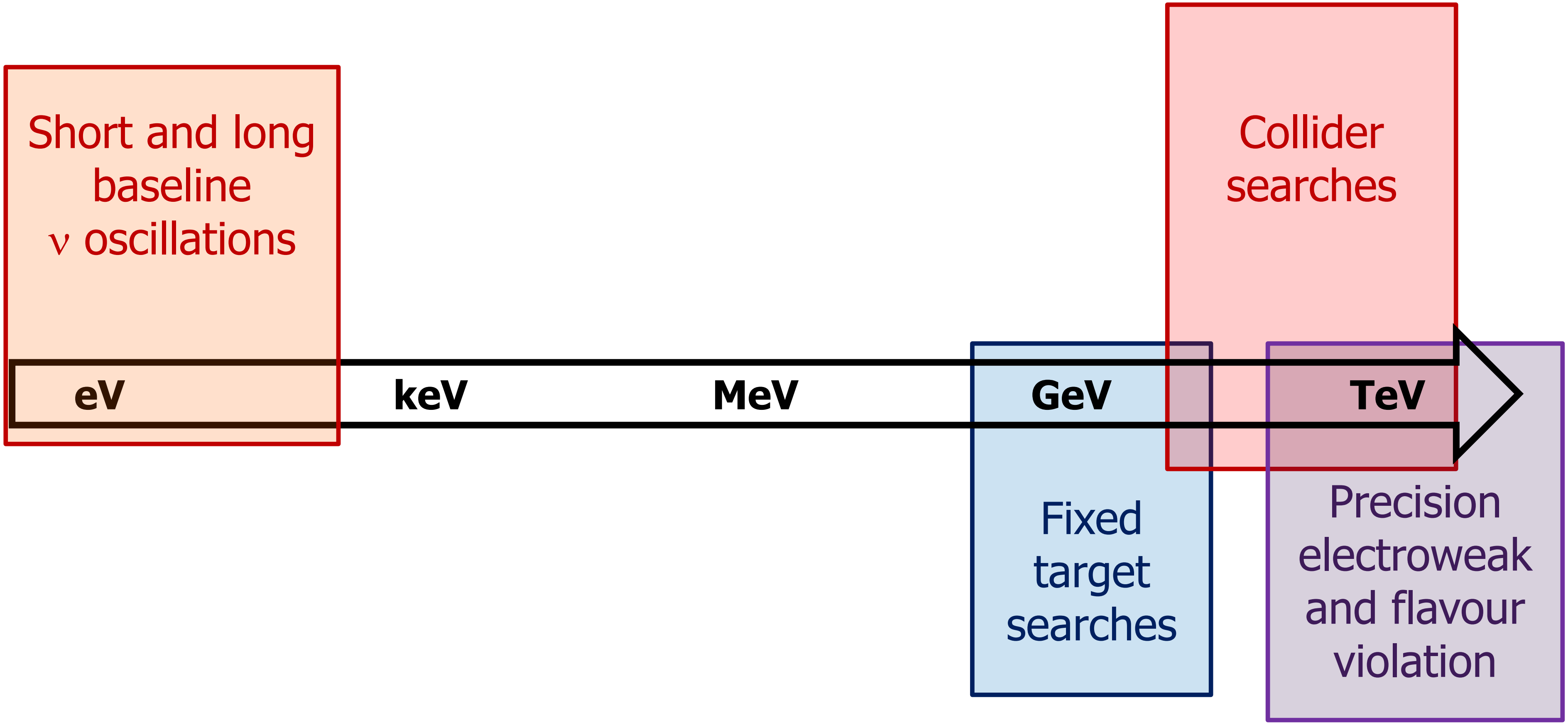


A new physics scale



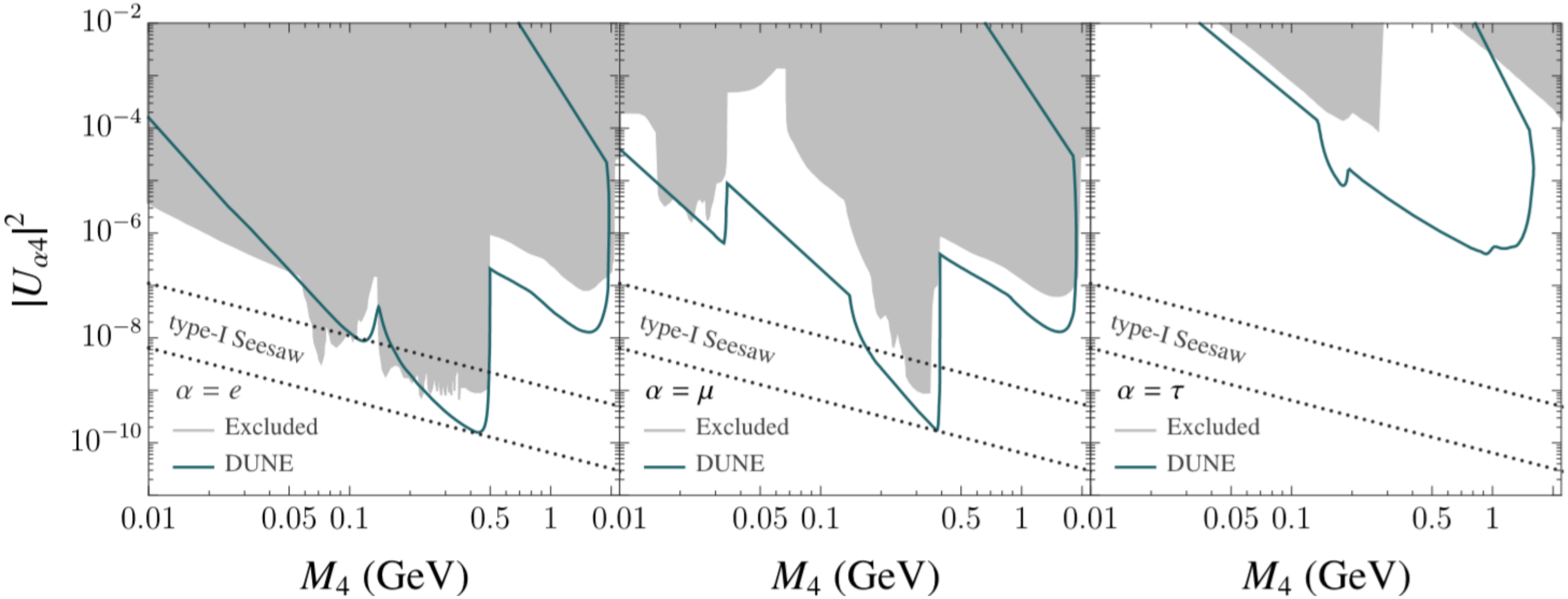
See talk by Xabier Marcano

A new physics scale



Looking for N_R: Beam Dumps

Sensitivity of DUNE ND to N_R



P. Coloma, EFM, M. González-López, J. Hernández-García arXiv:2007.03701

A FeynRules file with interactions between mesons and N_R (HNLs) is provided

See also: P. Ballett, T. Boschi, and S. Pascoli arXiv:1905.00284

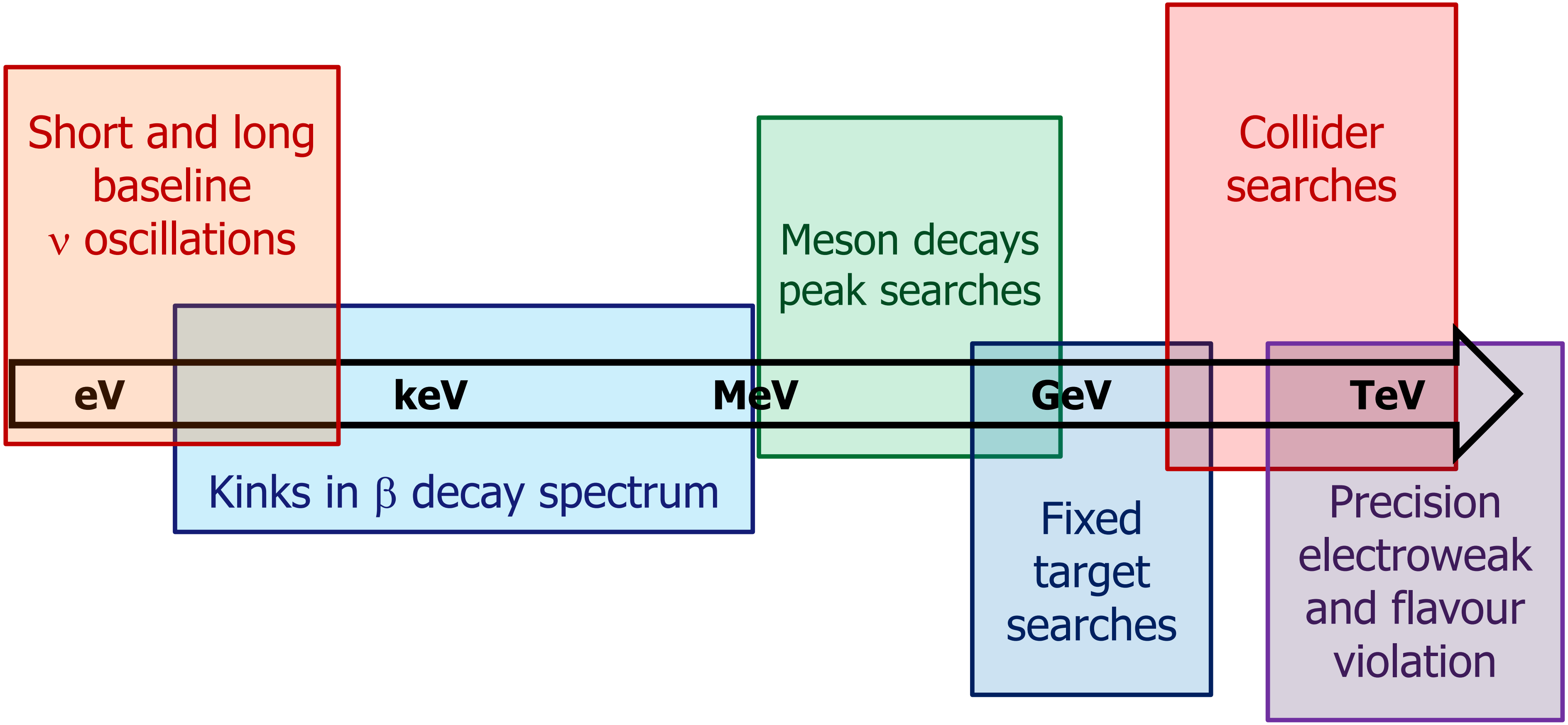
J. M. Berryman, A. de Gouvea, P. J. Fox, B. J. Kayser, K. J. Kelly, and J. L. Raaf arXiv:1912.07622

I. Krasnov arXiv:1902.06099

M. Breitbach, L. Buonocore, C. Frugiuele, J Kopp, L. Mittnacht arXiv:2102.03383

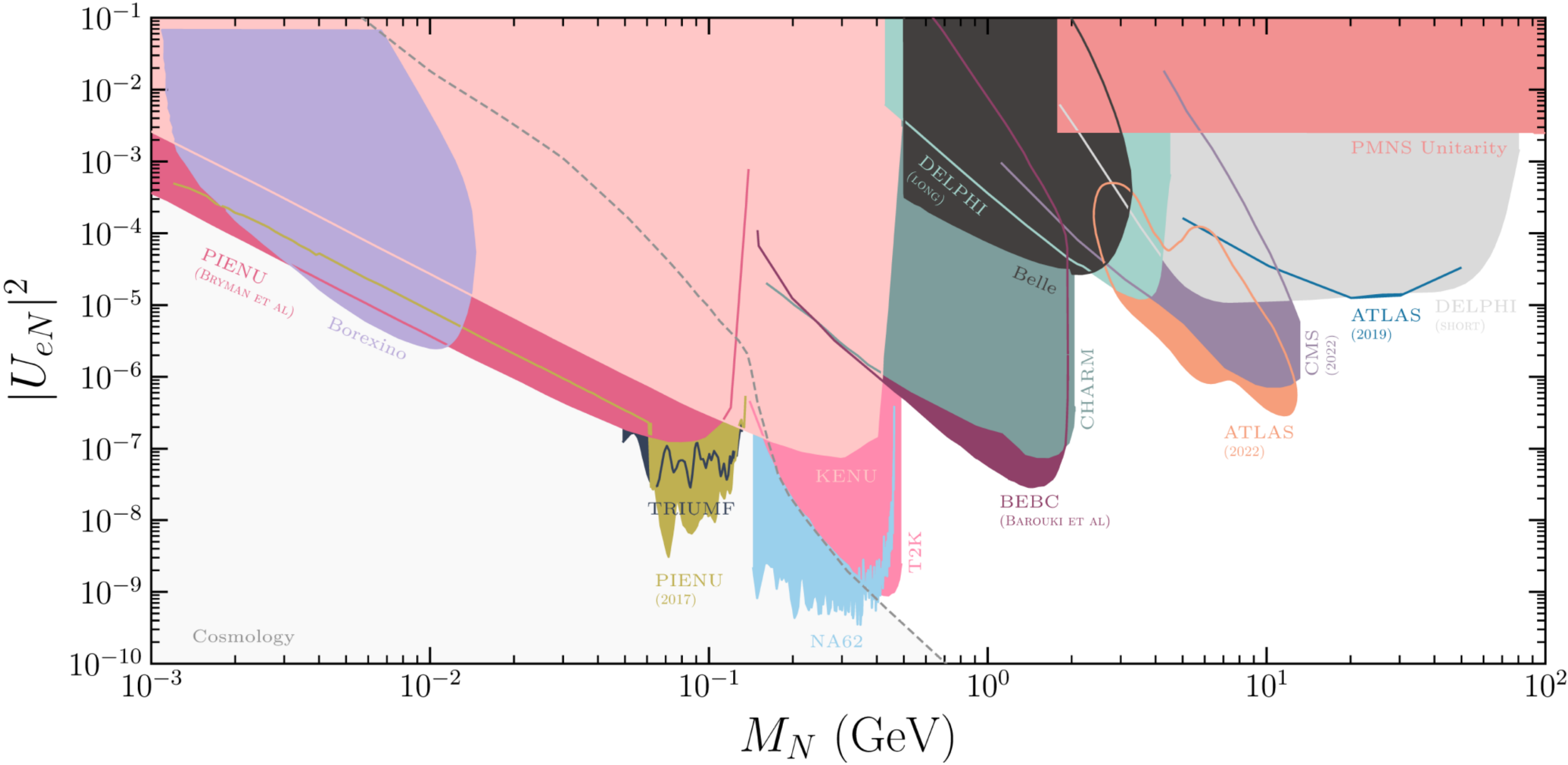
A. M. Abdullahi, P. Barham Alzas et al. arXiv:2203.08039

A new physics scale



Looking for N_R

All together:



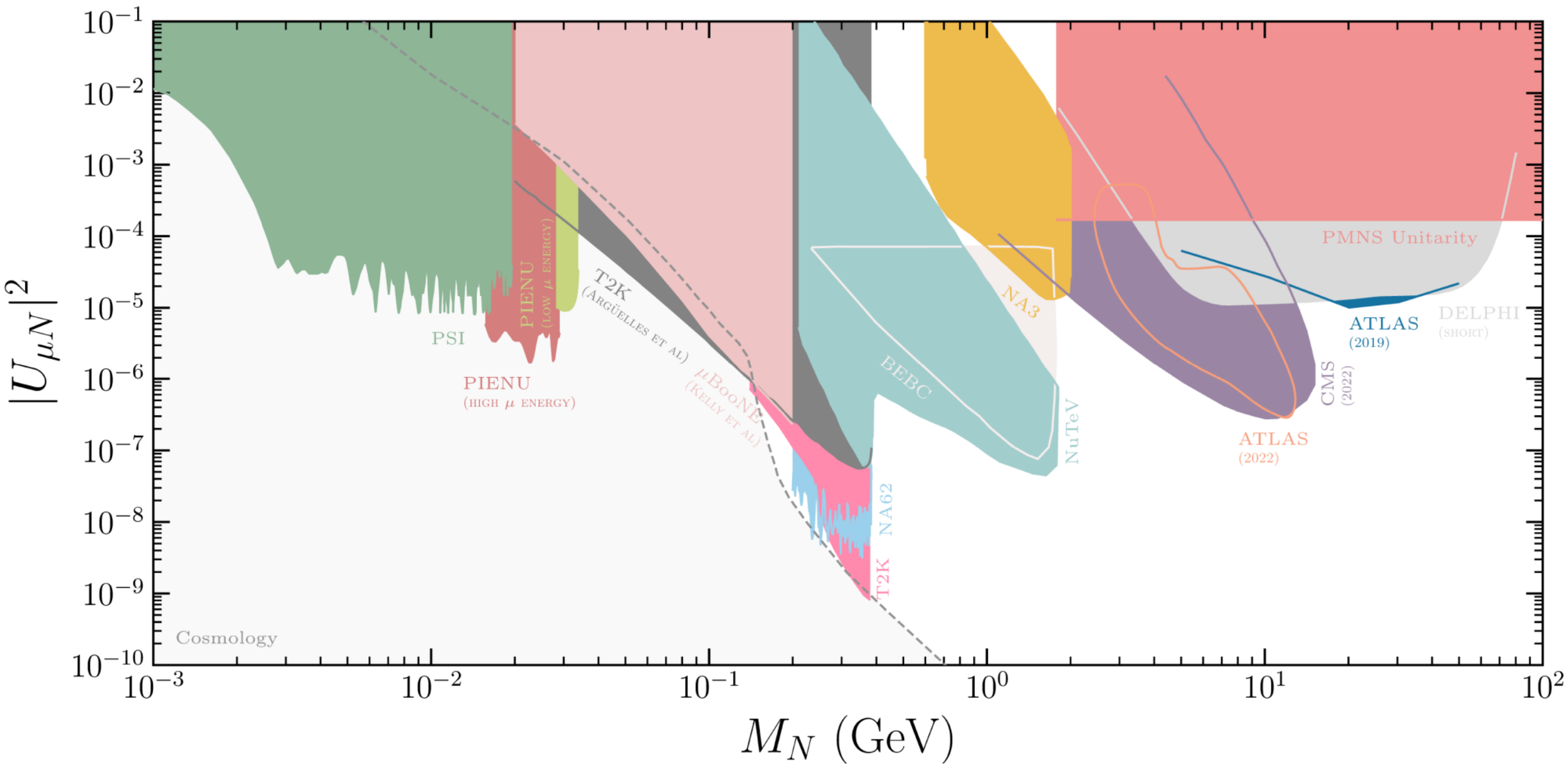
EFM, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón arXiv:2303.XXXXX

https://github.com/mhostert/Heavy-Neutrino-Limits

See also: P. D. Bolton, F. F. Deppisch and P. S. B. Dev arXiv:1912.03058

Looking for N_R

All together:



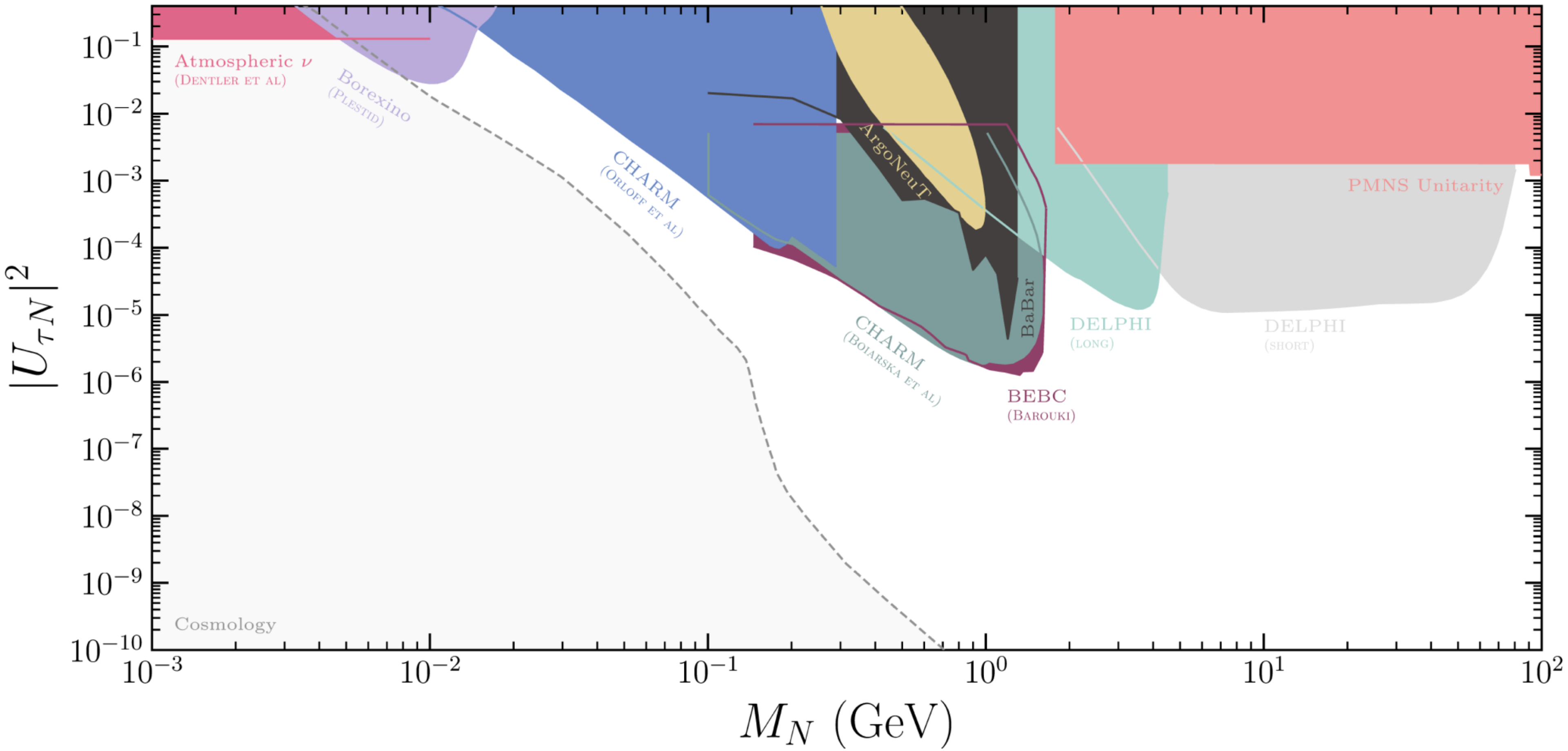
EFM, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón arXiv:2303.XXXXX

https://github.com/mhostert/Heavy-Neutrino-Limits

See also: P. D. Bolton, F. F. Deppisch and P. S. B. Dev arXiv:1912.03058

Looking for N_R

All together:

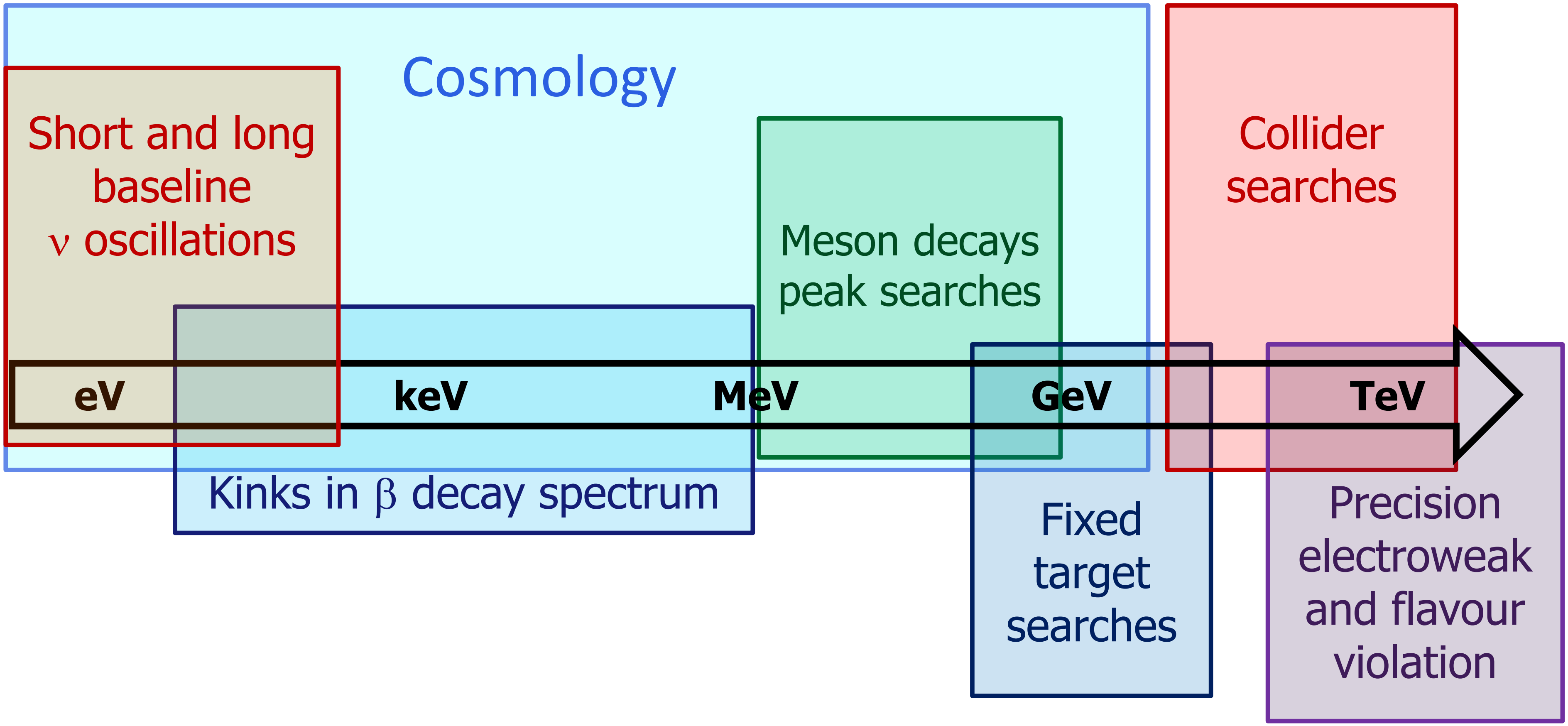


EFM, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón arXiv:2303.XXXXX

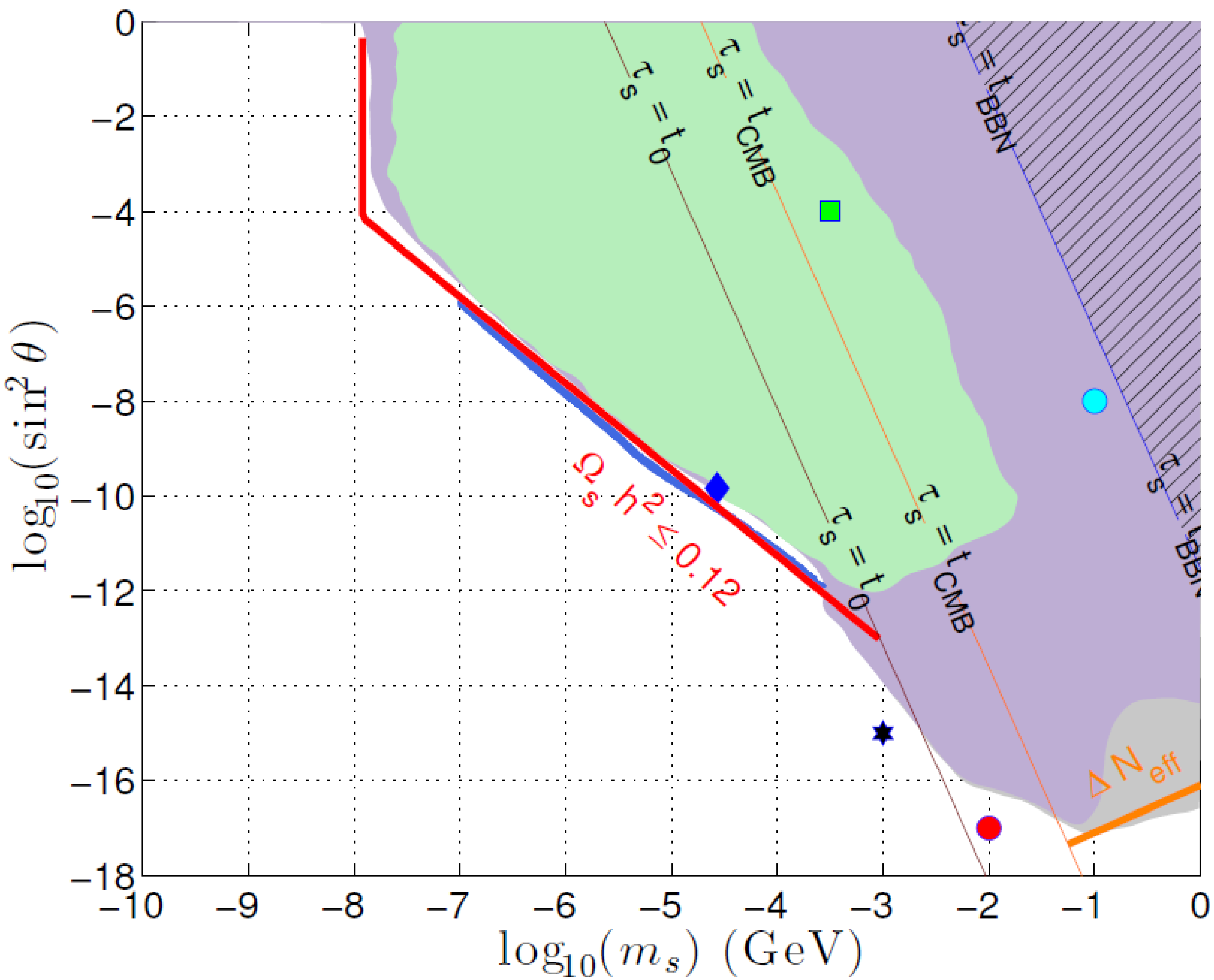
https://github.com/mhostert/Heavy-Neutrino-Limits

See also: P. D. Bolton, F. F. Deppisch and P. S. B. Dev arXiv:1912.03058

A new physics scale

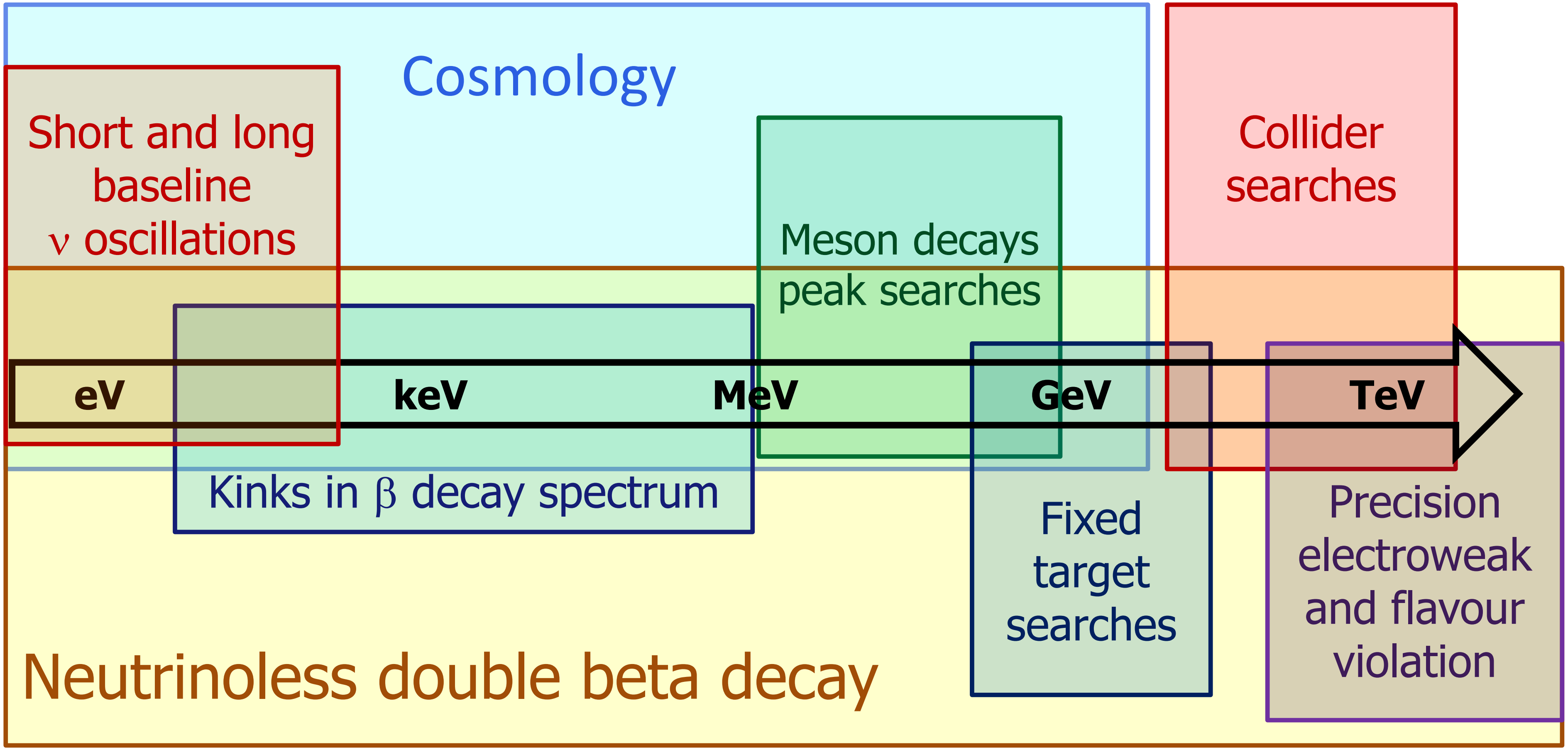


Cosmology



A. C Vincent, EFM, P. Hernandez, M. Lattanzi and O. Mena arXiv:1408.1956
See also K. Langhoff, N. J. Outmezguine, and N. L. Rodd arXiv:2209.06216

A new physics scale

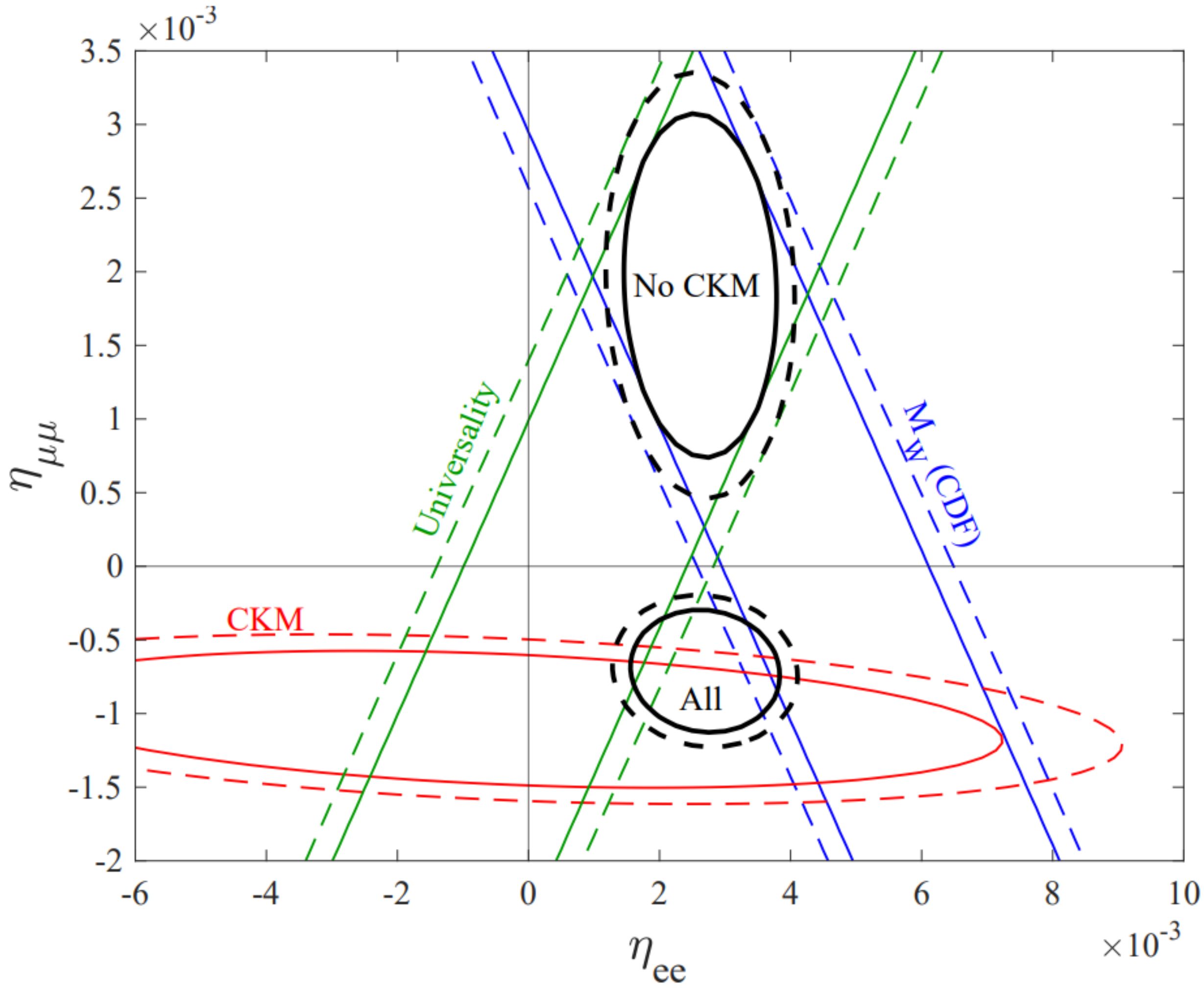


See talk by Patrick Bolton

Conclusions

- Neutrino masses and mixings imply new BSM physics
- The simplest extension, right-handed neutrinos, already imply a lot of new phenomenology to search for:
  - Non-unitarity, searches at colliders, fixed targets, cosmology, $0\nu\beta\beta$,…
- Also offers conexions to other open problems of the SM
  - Baryogenesis, Dark Matter, Flavour puzzle...

Non-unitarity and M_W from CDF



M. Blennow, P. Coloma, EFM, M-González-Lopez Phys.Rev.D 106 (2022) 7

Looking for N_R: Non-Unitarity

Or $N = (1-\alpha)\cdot U_{PMNS}$ with $(1-\alpha) = U_{36}U_{26}U_{16}U_{35}U_{25}U_{15}U_{34}U_{24}U_{14}$

$$\alpha \simeq \begin{pmatrix} \frac{1}{2}\left(s_{14}^2+s_{15}^2+s_{16}^2\right) & 0 & 0 \\ \hat{s}_{14}\hat{s}_{24}^* + \hat{s}_{15}\hat{s}_{25}^* + \hat{s}_{16}\hat{s}_{26}^* & \frac{1}{2}\left(s_{24}^2+s_{25}^2+s_{26}^2\right) & 0 \\ \hat{s}_{14}\hat{s}_{34}^* + \hat{s}_{15}\hat{s}_{35}^* + \hat{s}_{16}\hat{s}_{36}^* & \hat{s}_{24}\hat{s}_{34}^* + \hat{s}_{25}\hat{s}_{35}^* + \hat{s}_{26}\hat{s}_{36}^* & \frac{1}{2}\left(s_{34}^2+s_{35}^2+s_{36}^2\right) \end{pmatrix}$$

Triangular structure more convinient for oscillations

Z.-z. Xing 0709.2220 and 1110.0083.
F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1503.08879.

Dictionary

$$\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix} = \begin{pmatrix} \eta_{ee} & 0 & 0 \\ 2\eta_{e\mu}^* & \eta_{\mu\mu} & 0 \\ 2\eta_{e\tau}^* & 2\eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\beta\alpha}^{s*} = \epsilon_{\alpha\beta}^{d} = -\alpha_{\alpha\beta}$$

$$\epsilon_{ee} = -\alpha_{ee} \qquad \epsilon_{\mu\mu} = \alpha_{\mu\mu} \qquad \epsilon_{\tau\tau} = \alpha_{\tau\tau}$$

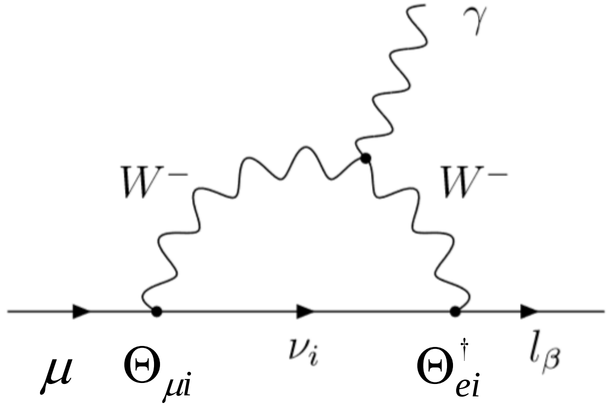
$$\epsilon_{e\mu} = \frac{1}{2}\alpha_{\mu e}^* \qquad \epsilon_{e\tau} = \frac{1}{2}\alpha_{\tau e}^* \qquad \epsilon_{\mu\tau} = \frac{1}{2}\alpha_{\tau\mu}^*$$

M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1609.08637

Probing the Seesaw: Non-Unitarity

All constraints are for the limit of very heavy extra neutrinos
OK for all processes except maybe the loop LFV

Cancellations of these diagrams explored in:
D.V. Forero, S. Morisi,
M. Tortola, J.W.F. Valle 1107.6009

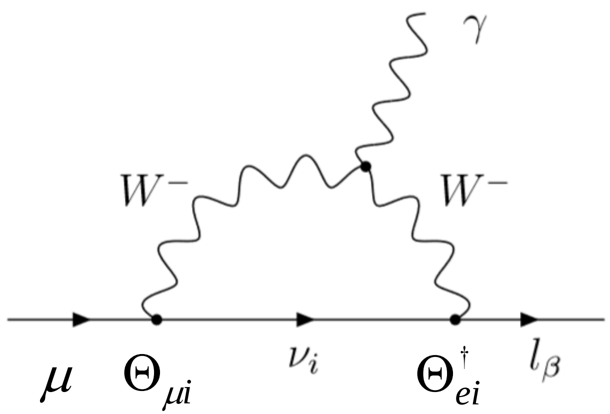


$$\Gamma \propto \sum_i \Theta_{\mu i} \Theta^\dagger_{ei} f\left(\frac{M_i^2}{M_W^2}\right)$$

Probing the Seesaw: Non-Unitarity

All constraints are for the limit of very heavy extra neutrinos
OK for all processes except maybe the loop LFV

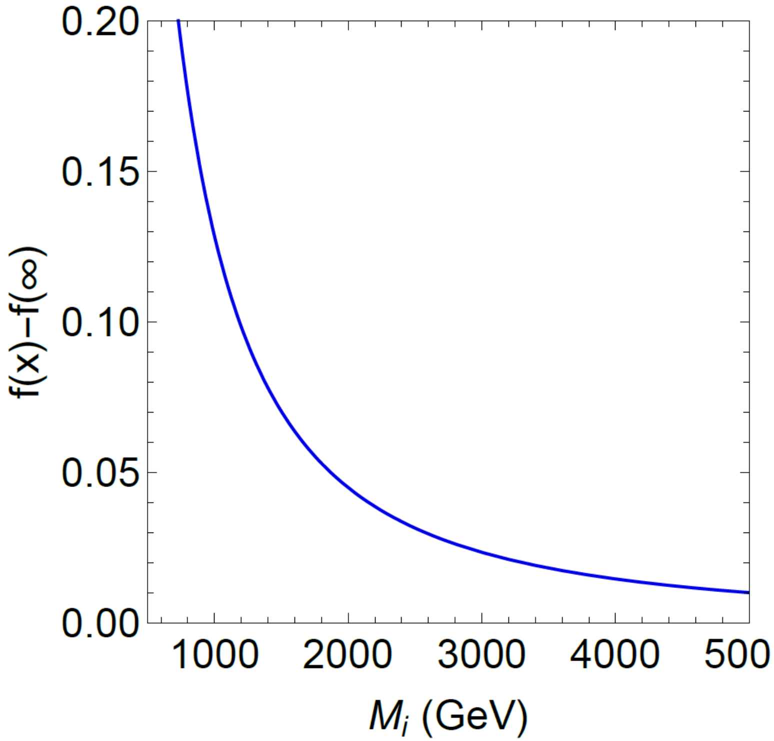
Cancellations of these diagrams explored in:
D.V. Forero, S. Morisi,
M. Tortola, J.W.F. Valle 1107.6009

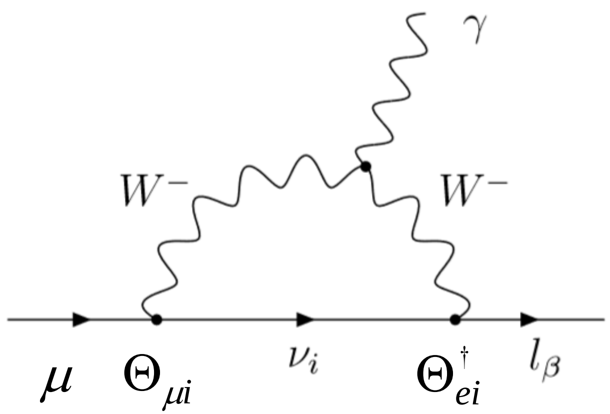


$$\Gamma \propto \sum_i \Theta_{\mu i}\Theta^{\dagger}_{ei} f\left(\frac{M_i^2}{M_W^2}\right) = 2\eta_{e\mu} f(\infty) + \sum_i \Theta_{\mu i}\Theta^{\dagger}_{ei}\left(f\left(\frac{M_i^2}{M_W^2}\right) - f(\infty)\right)$$

Probing the Seesaw: Non-Unitarity

All constraints are for the limit of very heavy extra neutrinos
OK for all processes except maybe the loop LFV

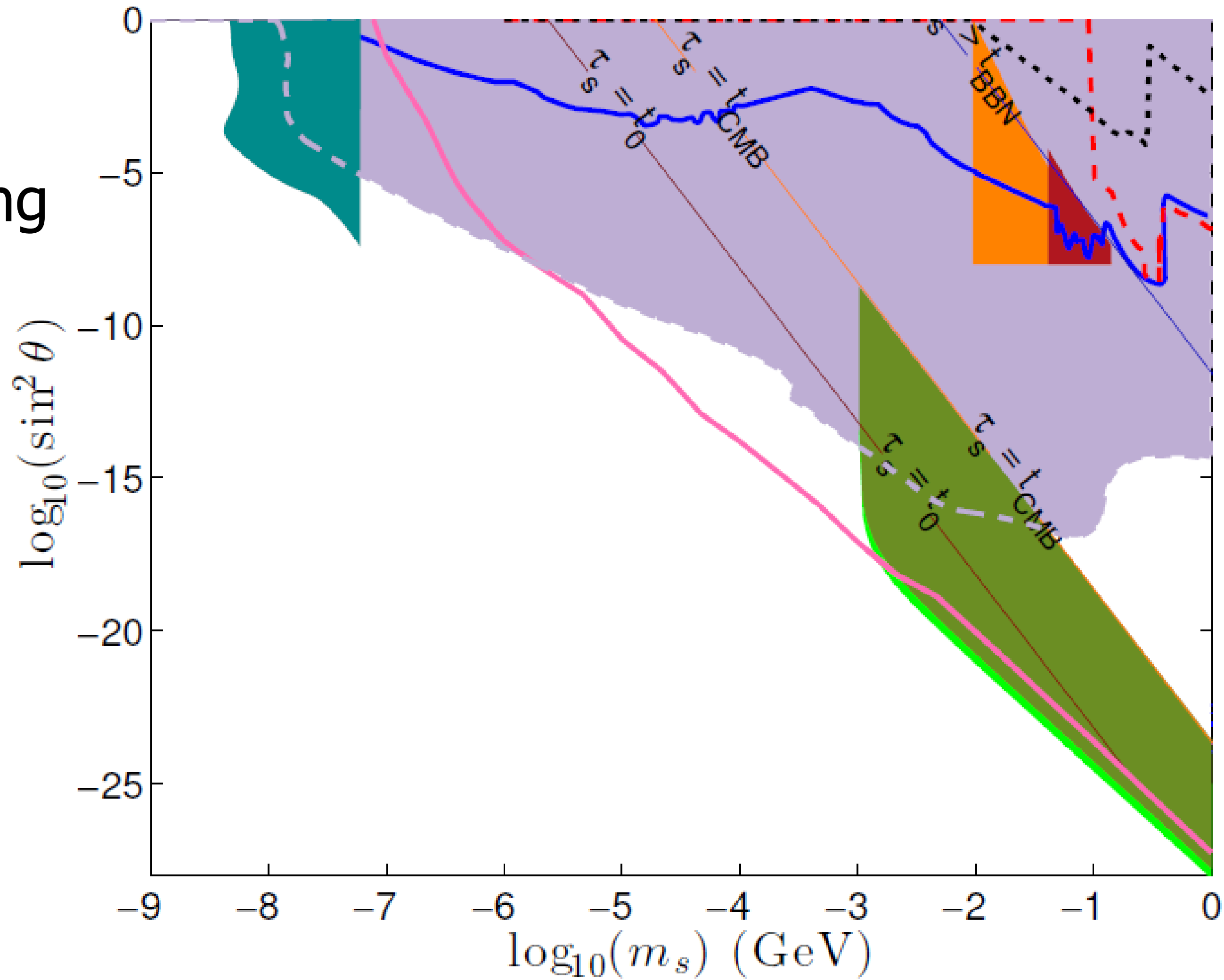




$$\Gamma \propto \sum_i \Theta_{\mu i}\Theta^\dagger_{ei} f\left(\frac{M_i^2}{M_W^2}\right) = 2\eta_{e\mu} f(\infty) + \sum_i \Theta_{\mu i}\Theta^\dagger_{ei}\left(f\left(\frac{M_i^2}{M_W^2}\right) - f(\infty)\right)$$

Cosmology and lab constraints

At intermediate scales very strong constraints from direct searches and cosmology



A. C Vincent, EFM, P. Hernandez, M. Lattanzi and O. Mena arXiv:1408.1956